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THESIS

SURVEY OF THE
QH-50 DASH SYSTEM

BY

Robert S. Paskulovich

June 1987

Thesis Advisor: H.A. Titus

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The role of RPV's as platforms for tactical reconnaissance is steadily growing in importance, and their development is receiving attention by aerospace industries the world over. This thesis focuses on the superannuated QH-50 DASH system, which has the potential for being refurbished and returned to useful operational serviceability. Of fundamental import to this end is the need to perfect the launch and recovery control systems of this aircraft. A survey is done of the system as it exists today, along with an investigation of its control system.

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Survey of the

QH-50 DASH System

by

Robert S. Paskulovich
Lieutenant Commander, United States Navy
B.S., Wayne State University, 1975

Submitted in partial fulfillment of the
requirements for the degrees of

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and
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ABSTRACT

The role of RPV's as platforms for tactical reconnaissance is steadily growing in importance, and their development is receiving attention by aerospace industries the world over. This thesis focuses on the superannuated QH-50 DASH system, which has the potential for being refurbished and returned to useful operational serviceability. Of fundamental import to this end is the need to perfect the launch and recovery control systems of this aircraft. A survey is done of the system as it exists today, along with an investigation of its control system.

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TABLE OF TERMS AND ABBREVIATIONS

A	lateral cyclic pitch (rad)
AFCS	Automatic Flight Control System
CG	center of mass
g	acceleration due to gravity
GW	gross weight
H	altitude (above mean sea level)
H_c	commanded altitude
HP	horsepower
I_{xx}	moment of inertia about roll axis
I_{yy}	moment of inertia about pitch axis
K	observer gain (continuous)
K'	observer gains (discrete)
L	moments about X axis
M	moments about Y axis
N	moments about Z axis
P	roll rate in body axis coordinates (rad/sec)
Q	pitch rate in body axis coordinates (rad/sec)
R	yaw rate in body axis coordinates (rad/sec)
rpm	revolutions per minute
RPV	Remotely Piloted Vehicle
S	Laplace operator
U	longitudinal velocity of vehicle CG in body axis coordinates (ft/sec)
V	lateral velocity of vehicle CG in body axis coordinates (ft/sec)
V_c	collective actuator voltage (volts)
W	vertical velocity of vehicle CG in body axis coordinates (ft/sec)
X	Longitudinal position of vehicle
X	body-fixed longitudinal axis
X_c	commanded longitudinal position, feet
X'	earth-fixed longitudinal axis
Y	body-fixed lateral axis
Y'	earth-fixed lateral axis
Z	body-fixed vertical axis
Z'	earth-fixed vertical axis
θ	RPV pitch angle (rad)
θ_v	pitch angle loop feedback voltage (volts)
θ_c	RPV collective control deflection
ϕ	RPV roll angle (rad)
ψ	RPV heading angle
ψ_c	commanded heading

I. INTRODUCTION

A. BACKGROUND

The use and evolutionary development of RPV's is increasing rapidly, and is likely to increase much further yet. The role of RPV's as targets has been well established; they are the cheapest and best way of producing the realism which is so necessary to train modern missile defenses of all kinds [Ref 1]. The extension of the role for RPV's to the more active area of ECM or over-the-horizon targeting is well within the grasp of modern technology and is being developed rapidly. In any military operation involving actual combat, the importance of timely, accurate intelligence regarding an enemy's position or posture cannot be overestimated. In addition, the value of this intelligence is greatly enhanced if the enemy does not know or suspect it has been collected. RPV's can be of inestimable value in this regard if they have the capability and reliability to provide real time intelligence and reconnaissance services to the field commander.

There exists today a large array of experimental projects, development projects and operational vehicles, including an old and tried concept in remotely piloted vehicles, the QH-5Ø DASH system. The disbanding of old

aircraft conceived in the past is a commonplace military event, particularly when it is very difficult to exercise a capability in any meaningful way. Aircraft in general, and the QH-50 in particular, are not isolated examples of cost-saving by removing old equipment from the inventory; the same happens to other important areas, such as electronic countermeasures and deception aids.

As for the future, some new claims are being made for RPV's, but recent operational history shows that in significant tactical operations they are still in their infancy. However, the alliance of modern existing technology with a really jam proof data link would open up wider operational uses for RPV's. In the case of the QH-50, if a perfected control system could be implemented, the platform could be further modernized by the installation of mission-specific gear, such as:

* increasing the fuel capacity
* fitting GPS navigation for precise positional information of the RPV
* active/passive EW equipment
* decoy and ELINT gear
* chaff dispensers
* acoustic-sensor dispenser
* reconnaissance packs
* target laser designators
* warloads

In all cases, modular payloads would increase flexibility. If equipped with high quality sensors capable of performing accurate surveillance and reconnaissance missions under a variety of environments and battlefield conditions, an RPV can perform vital services in areas where manned aircraft are either unavailable or would not survive. The QH-5Ø exists as an available, potentially adaptable vehicle without the expense and safety problems of building a new full-scale aircraft. However, the QH-5Ø system would require improvements and updates to be returned to operational service; this may not be able to be done inexpensively. The gas-turbine engine and mechanical machinery to drive the QH-5Ø coaxial rotor system are considered to be efficient and reliable, so any refurbishment considered would for all intents and purposes have to include control system updates, before any specific missions could be considered.

B. QH-5Ø DASH SYSTEM STATUS

Like other RPV's, if the QH-5Ø recovery system could be perfected, the number of highly skilled personnel required and the concomitant cost of training and keeping service craftsmen would be reduced. Recovering an RPV at the end of its mission calls for enormous know-how and ability on the part of those operating it. If only one in every two recoveries was successful, the cost of the system is clearly

too much; even success rates of 90% may not be cost-effective. Compounding the difficulties of recovery of an RPV at sea are the facts that the radio-guidance command on which RPV's rely is vulnerable to ECM (traditionally a specialty of Soviet forces), the ship's own electromagnetic environment, and the problems attendant to recovering in high winds and heavy seas.

The possibility exists for the U.S. Navy to give the obsolescent QH-50 aircraft a new lease on life, if they could be upgraded using cost-saving methods, even though there is no firm basic operating philosophy for this form of RPV.

Bringing the QH-50 back to operational service would require refurbishment of systems beyond the QH-50 itself. These systems include a control station to direct the RPV throughout its mission. Capabilities of the control station would include necessary gear to operate the vehicle, controls and displays of the sensors carried by the vehicle, and displays of the RPV position, utilizing data obtained either from the aircraft itself or from a tracking and communications unit. Such a tracking and communications unit should contain a jam-resistant data link, such as a spread-spectrum RF subsystem developed for approach control navigation, telemetry information transmission and command data link of the Hybrid Terminal Approach and Landing System.

C. SCOPE OF THESIS

This thesis surveys the QH-50 DASH RPV system, and the technical advancements that have made feasible the refurbishment of the QH-50. Specifically, information regarding the system is collated, and known flight behavior examined. A simplified math model based on the equations of motion is configured to simulate the QH-50, in order to provide qualitative insight into the response of the aircraft. Problems inherent with recovering rotary-wing aircraft on ships at sea are examined, and the prospects of allying state-of-the-art RPV control systems to the QH-50 to allow recovery in sea states up to 5 are considered.

II. DESCRIPTION OF THE QH-5Ø

A. BRIEF OPERATIONAL HISTORY

The QH-5Ø was built by the Gyrodyne Company of America to form the airborne component of the DASH (Drone Anti-Submarine Helicopter) weapon system. The QH-5Ø followed the successful development of a similar manned coaxial rotor helicopter built by Gyrodyne, the YRON-1 Rotorcycle [Ref 2]. The QH-5Ø DASH RPV was originally planned as part of the U.S. Navy's FRAM (Fleet Rehabilitation and Modernization) program, to add 8-1Ø years of useful life to about 14Ø World War II destroyers. The QH-5Ø first became operational on 7 January 1963. Over 5ØØ QH-5Ø drones had been delivered to the U.S. Navy by December 1966. The QH-5Ø is turbine powered; this gives it the advantage over gasoline-powered drones, because Navy ships carry JP fuel, but not avgas. The DASH was to be used to deliver torpedo warloads.

B. BASIC OPERATING CHARACTERISTICS

The QH-5Ø math model used in this thesis is the one developed in a study conducted by Lear Siegler, Inc. [Ref. 3], when the QH-5Ø was being considered as a platform for over-the-horizon reconnaissance on non-aviation ships.

The Gyrodyne QH-5Ø drone helicopter has a coaxial rotor system with counter rotating blades eliminating the need for a tail rotor. It has conventional helicopter controls - longitudinal and lateral cyclic pitch to control fore/aft and lateral motion respectively. Heave motion is controlled by collective pitch control. Yaw moments are generated by the aileron-like deflection of rotor blade tip brakes. No aerodynamic surfaces are provided. Stability augmentation is provided through an all axis stability augmentation system.

Stability and control data were generated by similarity with existing helicopters and corroborated by comparison to the limited data available. Specifically, force derivatives in forward flight were scaled from available S-58 helicopter data, as found in Reference 3. Selected parameters are given in Table I.

TABLE I

SELECTED DIMENSIONS AND GENERAL DATA

PARAMETER	QH-5Ø	S-58
BLADE RADIUS, FEET	1Ø	28
BLADES PER ROTOR	2	4
CHORD, INCHES	13(ROOT) 6.5(TIP)	16.4
SOLIDITY RATIO	Ø.Ø862	Ø.Ø622
ROTOR SPEED, RPM	61Ø	244
WEIGHT EMPTY, POUNDS	1172.5	
I_{YY}, SLUG-FT^2	213.8	
I_{XX}, SLUG-FT^2	15Ø.Ø	
WEIGHT, NORMAL	23Ø3	
I_{YY}, SLUG-FT^2	47Ø.Ø	
I_{XX}, SLUG-FT^2	33Ø.Ø	

Important differences between the AH-5Ø and conventional single-rotor helicopters are as follows. The pitching moment due to change in speed is large and destabilizing due to the high location of the rotors from the aircraft center of gravity. Absence of tail surfaces causes the angle of attack stability to be nearly zero, thus contributing to a statically unstable aircraft. Yaw rate damping is low due to the absence of a tail rotor. Directional static stability is almost zero because there is no vertical tail to provide a stabilizing moment; without a tail rotor there is no consideration given to tail rotor torque, I_{RX}.

As cited in Reference 4, the automatic flight control system of the QH-5Ø is considered to be controllable by the Hybrid Terminal Assist Landing (HYTAL) system, a technology demonstrator of an auto-landing system, although it is noted that a significant improvement would be to include an altitude control loop built around an acceleration sensor, which would be integrated to provide an altitude rate and altitude displacement signal. Better handling and control of the QH-5Ø hopefully would then accrue during the recovery and landing phases of a flight. The currently used barometric referenced system is susceptible to the deleterious effects of the air flow about the coaxial rotor system, because the barometric probe extends through the rotor shaft, and senses disturbances caused by the whirling

blades. The transients in pressure differentials stemming from rotor speed fluctuations may cause handling problems.

The currently flying AH-5Ø's, operated by the China Lake Naval Weapons Center's target operations group, are reported to be susceptible to turn reversal. When the QH-5Ø is being operated in the launch/recovery helicopter mode, the aircraft will translate in the direction the swashplate is tilted. The pitch and roll cyclic in this mode are zeroed, so a coordinated turn is locked out, and the aircraft will skid when commanded to turn. The control feedback system for turn coordination is one area that has room for improvement. During launch/recovery, the helicopter is operating in what is called maneuver mode. In this mode, pitch, roll, and altitude are commanded directly by the controller. However, when operated in the cruise mode, heading and altitude are commanded by the controller. When switching from one mode to the other, undesirable transients may occur unless the system being handed-off to is initialized to the same commanded heading as the system being handed-off from. Additionally, this commanded heading may itself not be the same as the direction in which the QH-5Ø is desired to be flown. In a similar manner, the existence of large winds during the handoff procedure may necessitate the initialization of control parameters other than heading, such as velocity or attitude, prior to handoff to preclude unwanted transients.

III. MODEL BASED UPON EQUATIONS OF MOTION

A. QH-50 EQUATIONS OF MOTION

A math model was developed for the AH-50 derived from the basic equations of motion, as delineated in Roskam [Ref. 5]. This program was used to aid in the understanding of the QH-50 flight dynamics; it is an approximate and somewhat crude mathematical model intended to provide qualitative insight into the behavior of the QH-50. Reference 3 indicates that an airframe transfer function program, AFTF, was used to compute the denominator, numerator, and coupling numerator factors based on the aircraft stability derivatives, which were scaled from S-58 helicopter data, and on the longitudinal and lateral equations of motion.

It is characteristic of such airframe transfer function programs that they are modular in construction. First of all, the aircraft is divided into elements, with the physical characteristics of each element specified in the input data. The influence of each element on the aircraft is then summed to calculate dynamic characteristics of the assembled flight vehicle.

When an element (e.g., rotor) produces a force (lift, drag, thrust), the air in the vicinity of the aircraft is

set in motion. The induced velocities (downwash and sidewash) affect other elements by changing their local airspeed and angle of attack. Interference velocities are thus important and must be calculated accurately. Since the QH 50 has no tail rotor or vertical tail, and is skeletal in construction, aerodynamic coefficients obtained are functions of the rotor only.

The equations of motion used derive from Newton's law applied to six degrees of freedom, as in the case of fixed-wing aircraft. The equations contain inertia, gravity and aerodynamic forces. The equations are simplified by pretending a plane of symmetry. That is, it was assumed that fore-and-aft and vertical translations, as well as angular pitching motions are not "coupled" with sideways translations, nor with rolling and yawing.

A change in thrust affects side force, and rolling velocity affects thrust; these and other cross-effects are usually weak and are safely ignored [Ref. 5]. Furthermore, the assumption of small perturbations relieves us of nonlinearities as well as coupling, which are exhibited for large deflections such as rapid rolls, tight turns and large amplitude maneuvers. These predictions require wind-tunnel or emperical data.

Once the model was developed, it was coded into a Dynamic Simulation Language (DSL) program that approximates the QH-50 system.

B. DEVELOPMENT OF THE MODEL

In this math model, the X-Y plane is selected to coincide with the plane of symmetry of the aircraft, so that the products of inertia I_{xy} and I_{yz} equal zero. Since the QH-50 does not have a tail rotor, there are no considerations of rotor torque. The exact value of I_{zz} (moment of inertia about the vertical yaw axis) was not available; a value of 220 was assumed.

The definitions of the vector components used in this math model are shown in Figure 3.1. The orientation of the aircraft is depicted in Figure 3.2. The body-fixed coordinates are obtained in the following manner, as indicated in Figure 3.3: translate the earth-fixed coordinate system parallel to itself until its origin coincides with the center of mass of the aircraft. Then three consecutive rotations are performed. First the translated coordinate system is rotated about the Z-axis over an angle ψ, the heading (or yaw) angle. The resulting coordinate system is rotated about the Y_2-axis over an angle θ, the attitude (or pitch) angle. The resulting coordinate system is then rotated about the X_3-axis over an angle ϕ, the bank (or roll) angle. The angles ψ, θ, and ϕ are frequently referred to as the Euhler angles. These Euhler angles are used to perform coordinate transformations as shown in Roskam and indicated below in Figure 3.4.

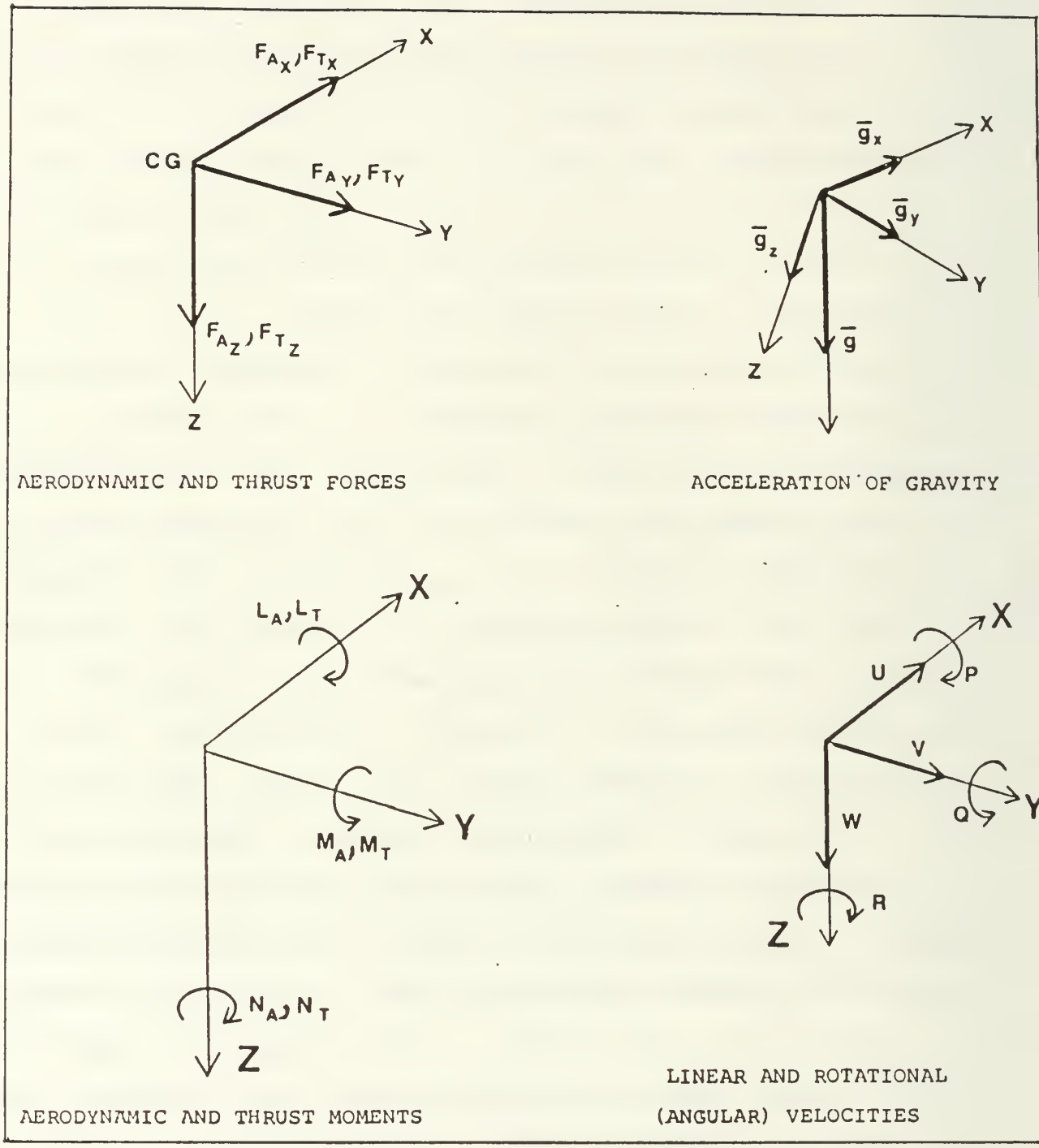

Figure 3.1

Definition of Vector Components

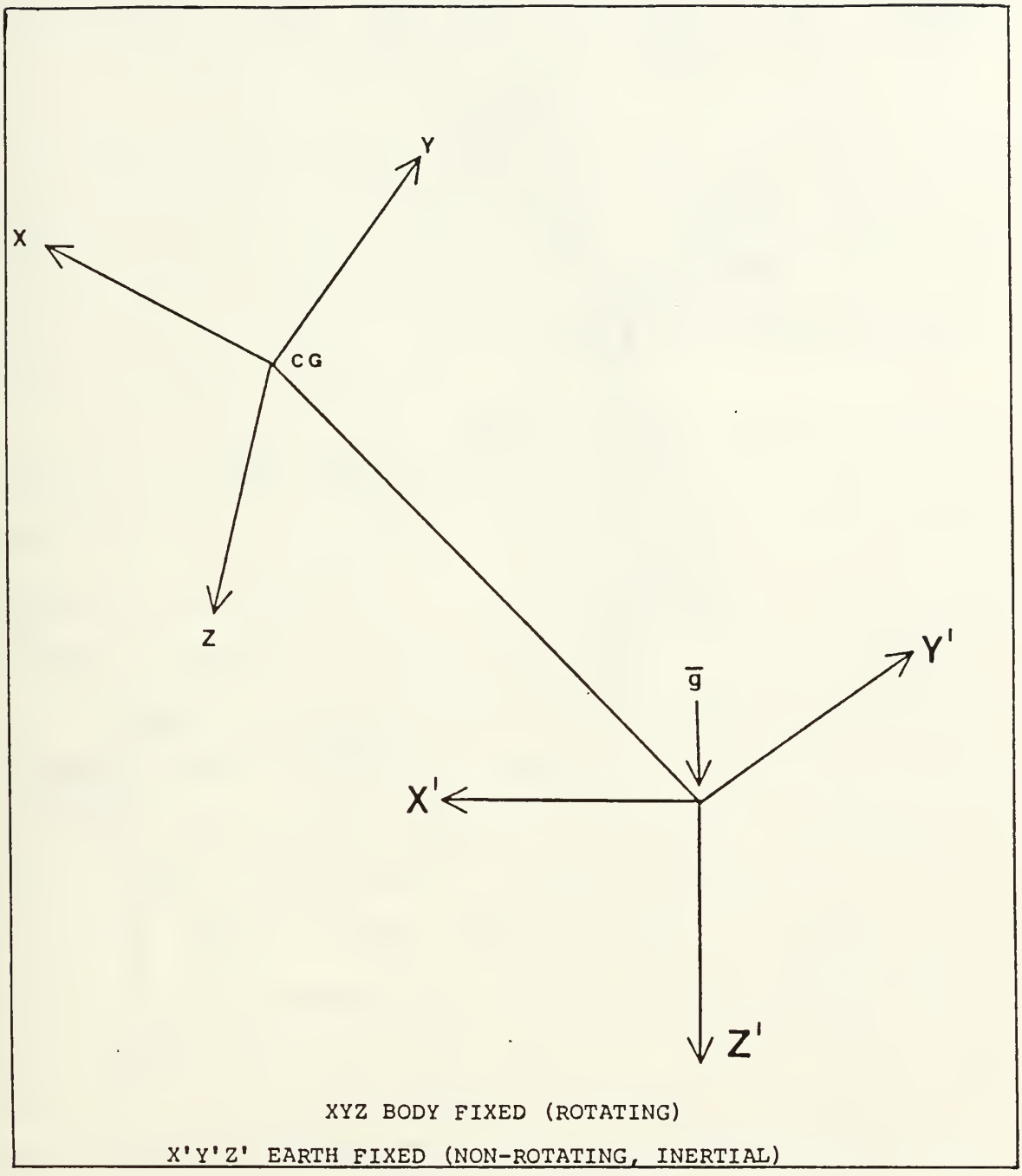

Figure 3.2

Coordinate Axes

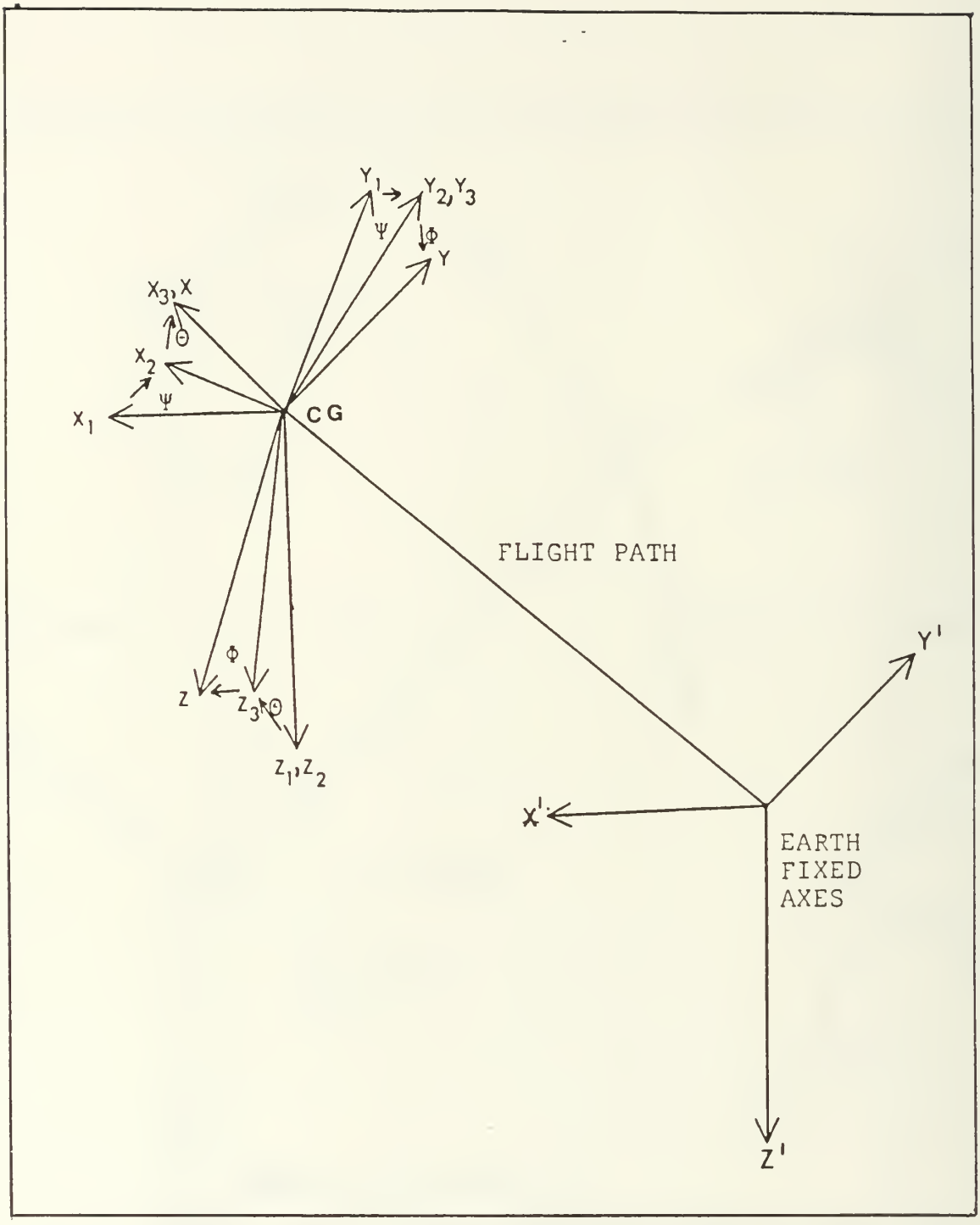

Figure 3.3

Orientation of Aircraft

$$\begin{Bmatrix} X' \\ Y' \\ Z' \end{Bmatrix} = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\theta & 0 & \sin\theta \\ 0 & 1 & 0 \\ -\sin\theta & 0 & \cos\theta \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi & -\sin\phi \\ 0 & \sin\phi & \cos\phi \end{bmatrix} \begin{Bmatrix} X \\ Y \\ W \end{Bmatrix}$$

Figure 3.4 Coordinate Transformation Matrix

Differential moment, force and angle equations are set up in body-fixed coordinates, then integrated and suitably transformed to yield rotational and linear velocities, as well as pitch, roll and yaw angles. The complete simulation code is listed in Appendix A.

The link between the longitudinal and lateral equations of motion and the airframe transfer functions is the program AFTF, as previously noted. The specifics of how this program works or how it is invoked are not considered here;the transfer functions obtained are listed in Reference 3. However, the equations of motion thus developed comprise a set of linear differential equations, which yield a very simplified model that is generic in nature. The program is initialized to simulate a QH-50 aircraft in a hover condition. One of three possible sets of inputs may be chosen to run a simulation: 1) All force and moments set to zero, 2) Any of the three cardinal forces set to any arbitrary values while holding all moments to zero, or 3) Any of the three moments set to any arbitrary values while holding all forces equal to zero. The equations are decoupled. The chosen combination of inputs are input via a parameter statement, in which rotor rpm and acceleration may

also be specified. The force and moment inputs act upon the vehicle's center of gravity.

C. RESULTS OF THE MODEL

Any variety of arbitrary forces and moments may be looked at. Figures 3.5 through 3.7 show the behavior of the model in response to 100 pound forces applied in each of the body-fixed axes; Figures 3.8 through 3.10 show the behavior of the model in pitch, roll and yaw in response to moments applied about each of the body-fixed axes.

In Figure 3.5, the velocity response along the body-fixed X-axis to a 100 pound force applied for 5 seconds is shown. The graph indicates that acceleration occurs for the 5 seconds during which the force is applied, then reaches a steady-state value.

Figure 3.6 indicates the response to a 100 pound force applied along the body-fixed Y-axis for 5 seconds. As expected, given the simplifying assumptions used to derive the equations of motion, the response is identical to that seen in Figure 3.5.

Figure 3.7 shows the groundspeed response to the forces mentioned above; the groundspeed shown pertains to the earth-fixed (inertial) coordinated system.

Figure 3.8 shows the pitch response to a 10 slug-ft^2 positive moment about the pitch axis applied for 5 seconds. The pitch angle increases slightly while the moment is being

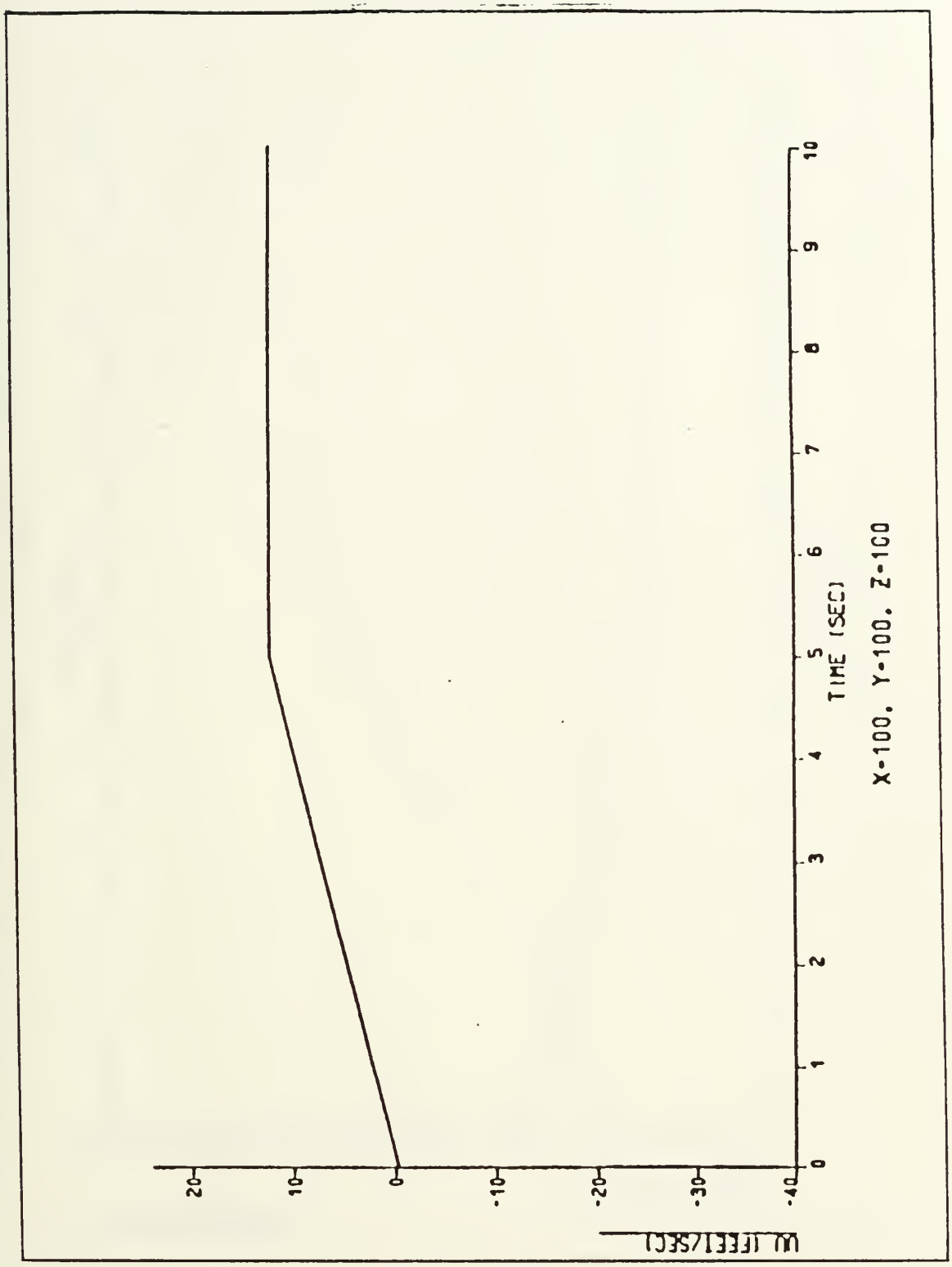

Figure 3.5 Response to 100-Pound Force in X-Axis

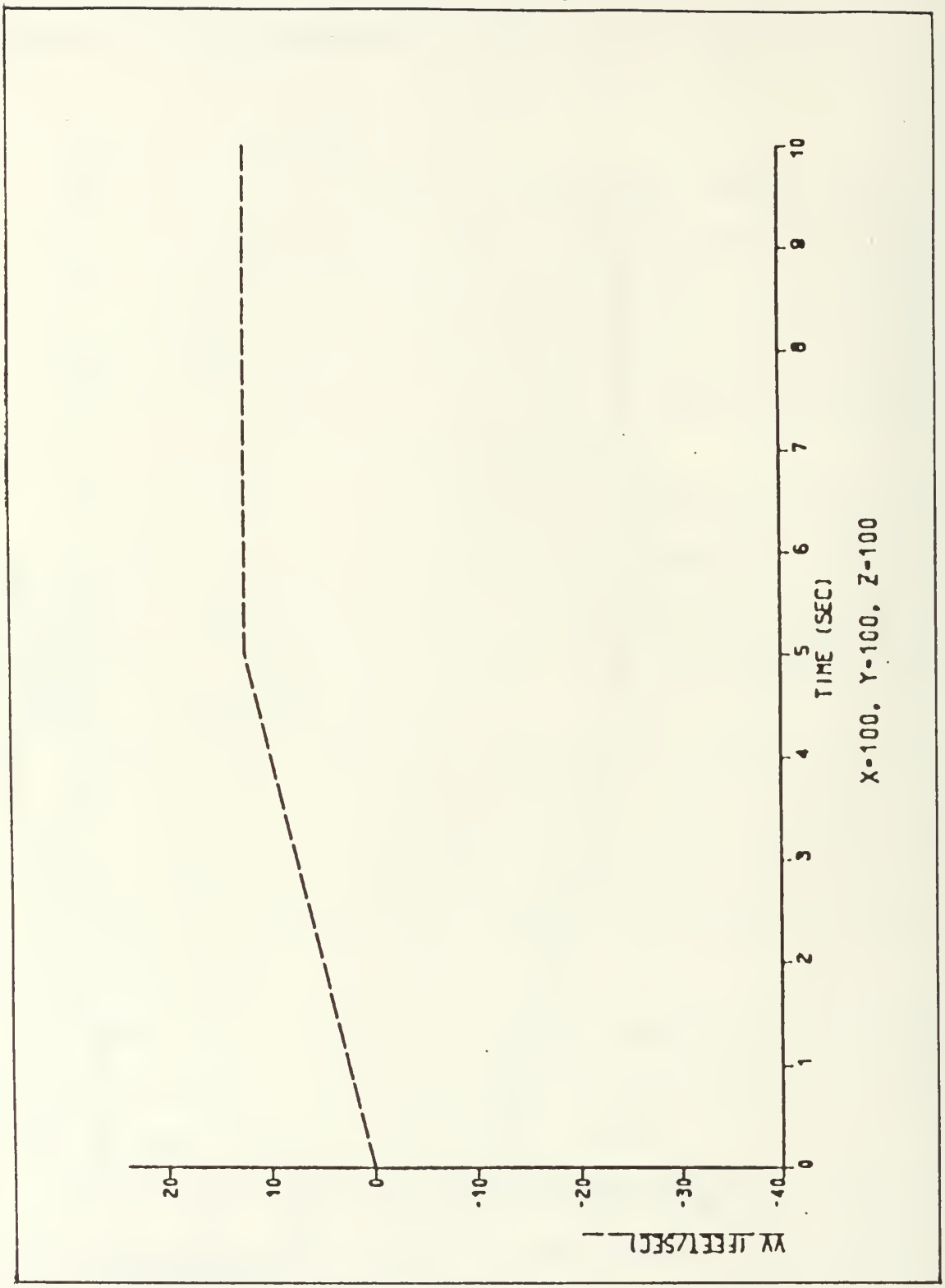

Figure 3.6 Response to 100-Pound Force in Y-Axis

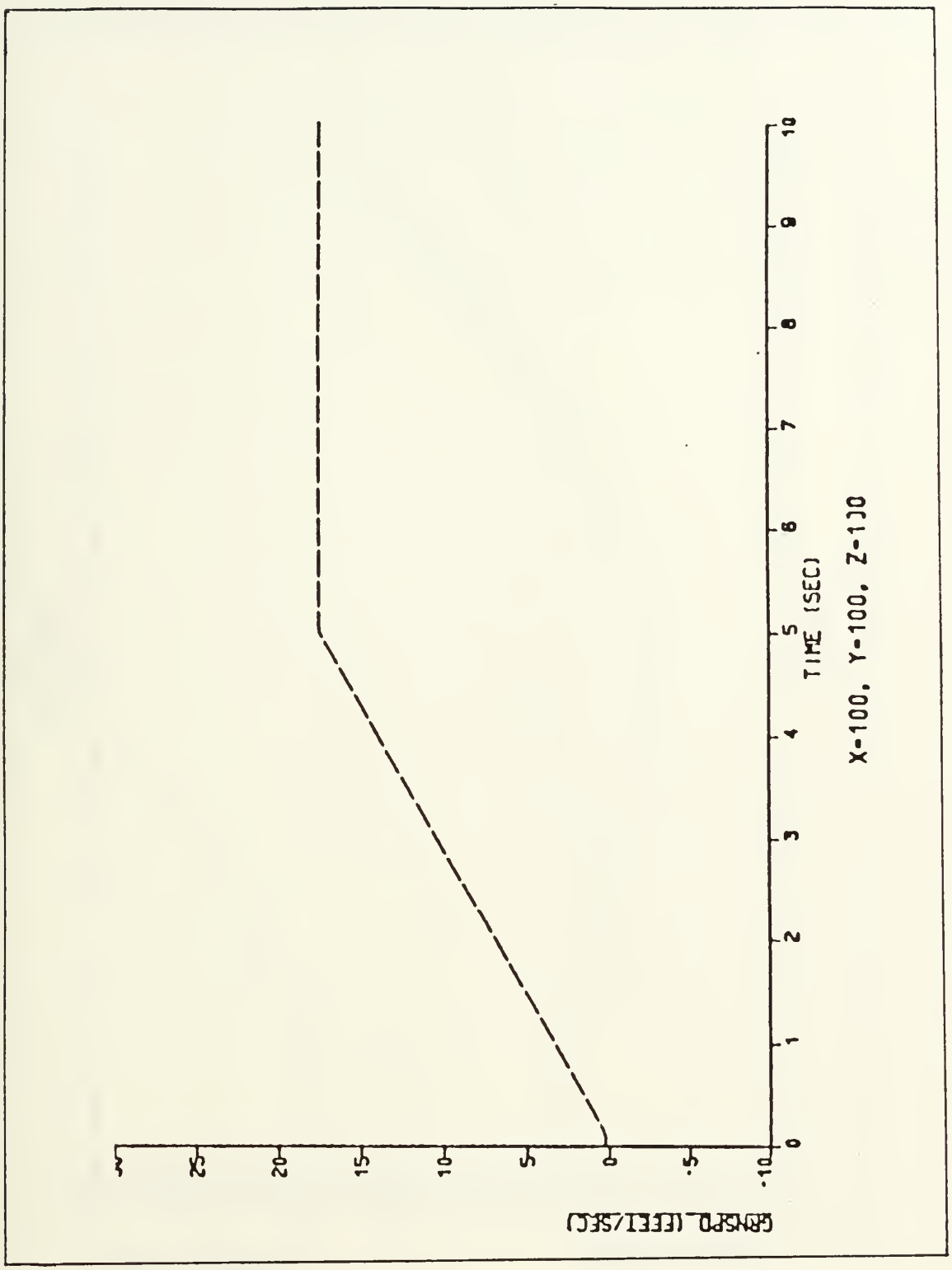

Figure 3.7 Groundspeed in Earth-fixed (Inertial) Axes

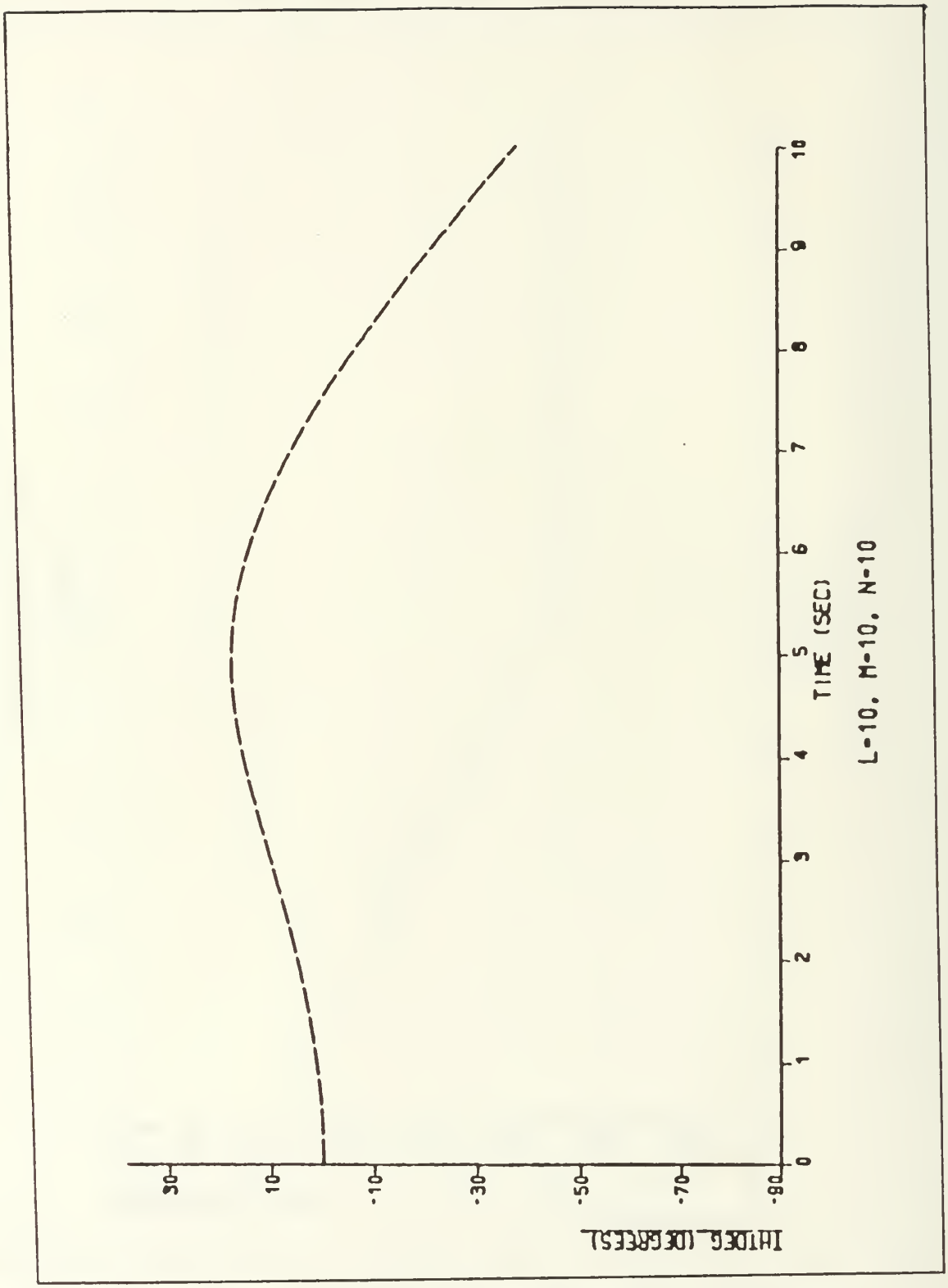

Figure 3.8 Pitch Response to 10 ft-lb Moment

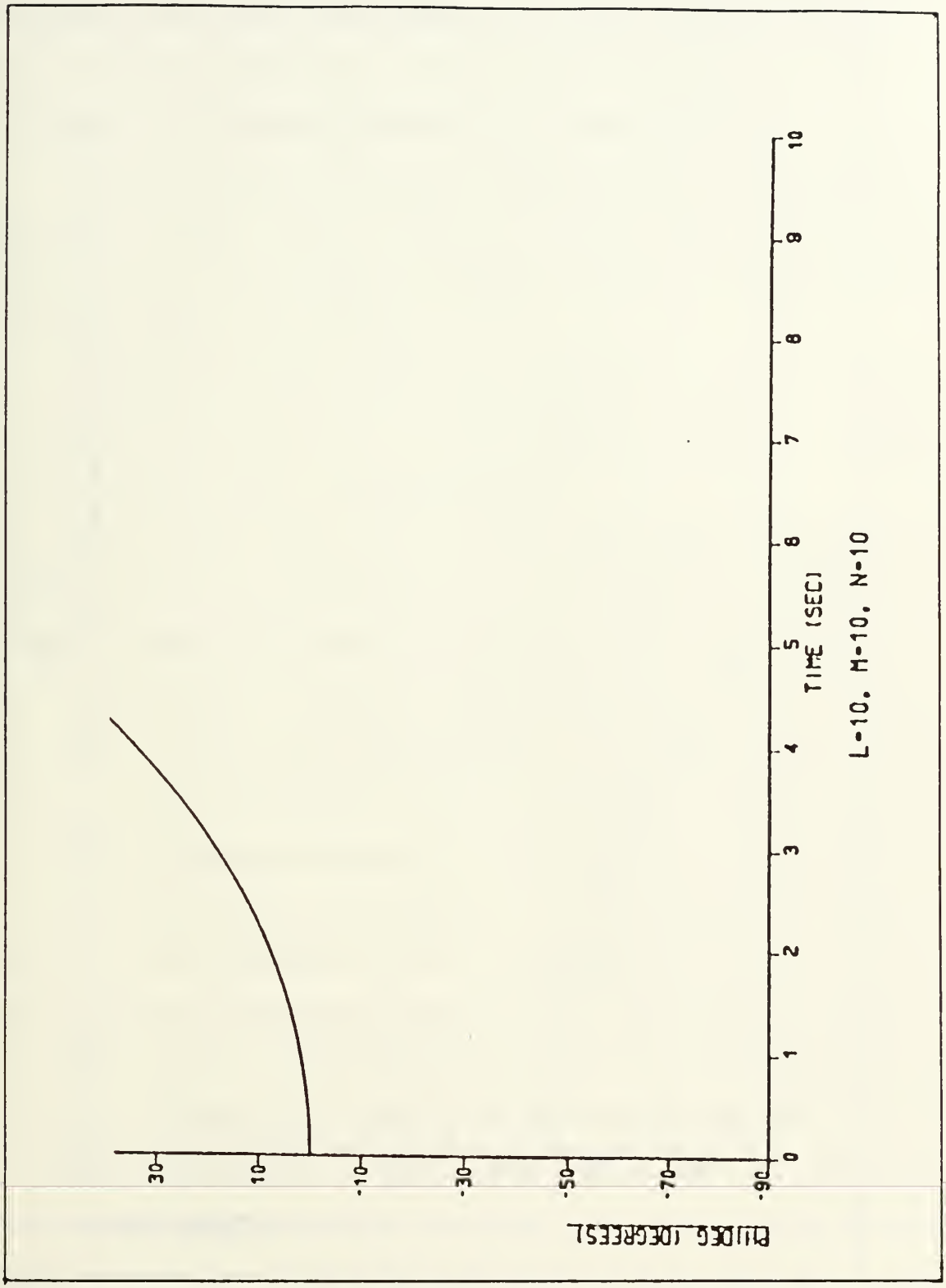

Figure 3.9 Roll Response to 10 ft-lb Moment

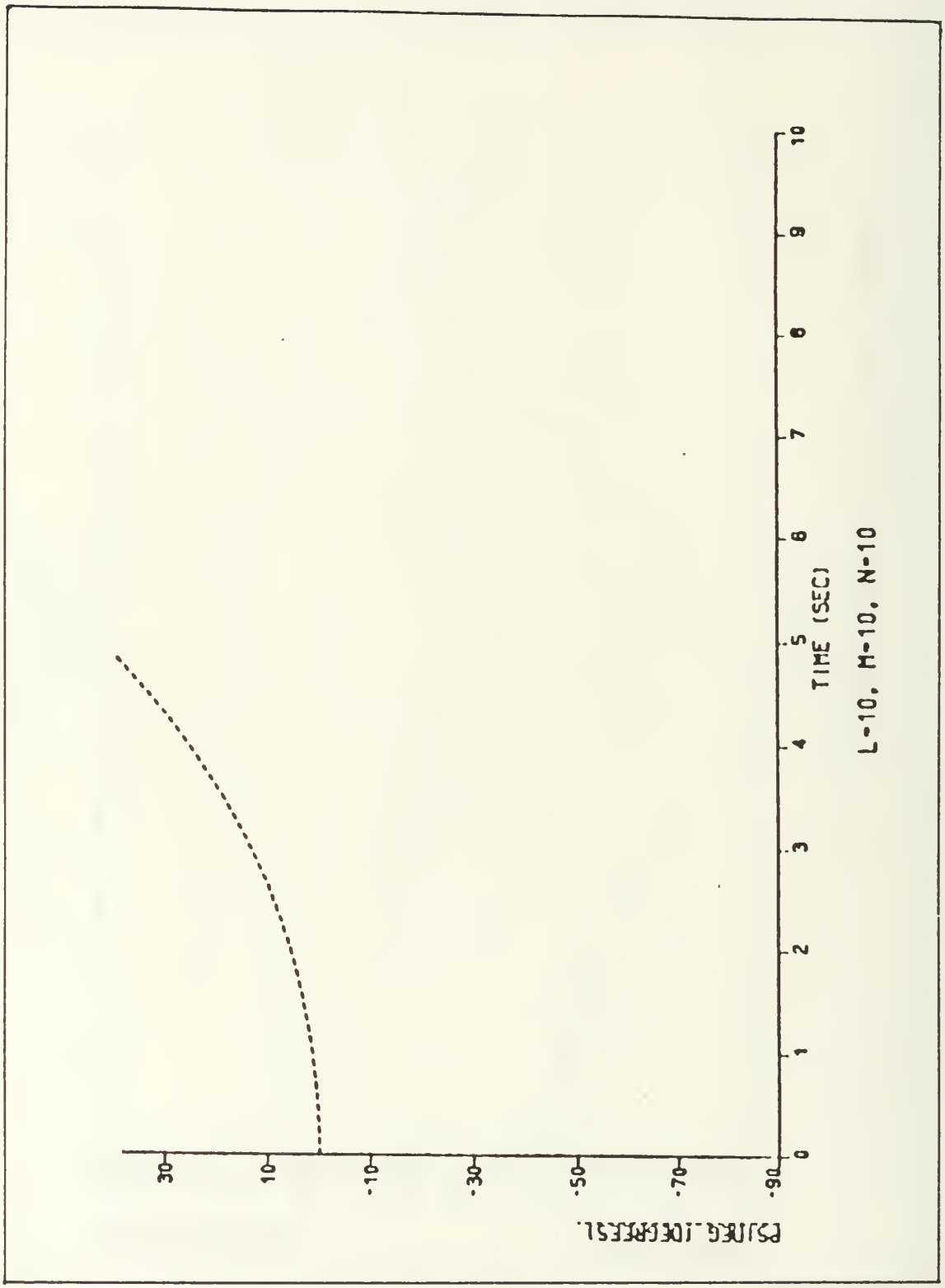

Figure 3.10 Yaw Response to 10 ft-lb Moment

applied. When the applied moment is removed, the aircraft pitches nose down. This simplified model does not take into account damping effects, so that after the applied moment is removed, the response becomes an undamped sinusoid.

Figure 3.9 shows the roll response to a 10 slug-ft^2 positive moment about the roll axis. The roll angle increases while the moment is being applies, then decreases when the moment is removed.

Figure 3.10 shows that the heading angle increases during the application of a 10 slug-ft^2 positive moment about the yaw axis, as was expected.

In all these cases, it is only the initial response of the model we are interested in; it is very simplified, and does not apply to large perturbations, which must be studied in a wind-tunnel or from flight studies of the actual aircraft. At any rate, development of the this QH-50 model based on the equations of motion provides insight into how the QH-50 transfer functions were derived in Reference 3, which mentioned the importance of these equations only in passing while omitting their development entirely. This again points to the fact that much of the recent work that has been done on the QH-50 has been accomplished despite the scarcity of aerodynamic data provided by the manufacturer of the QH-50, Gyrodyne. As cited in Reference 3, data were gleaned from all possible sources and compiled to form a basic data bank. Stability and control data were generated

by similarity to existing helicopters and the results corroborated by comparison to the limited data available. For the purposes of this study, those results are taken as a basis for subsequent chapters; corroborating their validity independently is beyond the scope of this thesis.

IV. THE LANDING PROBLEM

A. GENERAL CONSIDERATIONS

The ultimate criterion of a successful recovery is a controlled touchdown on the intended point of landing. The QH-50 has a skid landing gear fitted to its steel-tube chassis; landings on ship become difficult because the landing zone is not stationary.

The total energy of a compound rotor system in descent is composed of its potential energy due to its altitude, kinetic energy due to the velocity of the mass, and the rotational energy in the rotors. This energy can be used to substantially retard the horizontal and vertical velocities for touchdown. The kinetic energy of translation is used for "cyclic" flare, whereas the rotational energy of the rotor is used for "collective" flare.

Cyclic flare is performed by commanding an aft tilt of the rotor. This maneuver not only tilts the rotor force vector aft, but increases the force by tending to speed up the rotor. The speed-up may be permitted, is so desired, or the blade pitch can be increased to maintain rotor speed constant. Either action will increase the rotor speed retardation. The tilted and increased force resolves into components retarding the horizontal and vertical velocities.

Collective flare also may be used alone or in conjunction with cyclic flare to retard the vertical descent. By commanding a rapid and collective increase of blade pitch to near-stall values, a transient increase in rotor lift is produced. This action causes rotor rpm to drop off. Thus, flare performance is dependent on rotor kinetic energy, i.e., on rotor rpm at the beginning of the maneuver and the inertia of the rotors.

If the collective flare is performed after glide and cyclic flare, the vertical rate of descent will have been retarded partially, leaving less work to be performed by the rotors in collective flare. Collective flare from vertical descent is desirable in the case of the QH-50, which will be landing aboard a ship at sea in a small landing zone.

As an aside, during power-off descents, when the rotor-craft's drag essentially equals the vehicle weight, the system will be at is equilibrium rate of descent. The drag coefficient varies with flight speed, rotor solidity, and blade coning, and is maximum at low speed. However, it is not the present concern to investigate the case of autorotative descent and landing; a basic premise is that the QH-50 will have full power available during all phases of the recovery.

It is overly optimistic to expect that an operator manually controlling a QH-50 could smoothly land it on a ship at sea in any but the calmest of sea states (i.e., sea

state 2 or less). Even under these benign conditions the tendency of the rotors is to produce its own gusty air, as recirculation can occur in its own rotor wake. Adding to this are the unseen currents as the ambient wind gets distorted by the ship's structure or other obstructions. Nonuniform flow patterns may require nonstandard collective or cyclic positions that would surprise an unsuspecting controller.

For example, if, because of recirculation, the downflow is stronger on the left side, the aircraft may tend to move backward because of the ninety-degree lag in flapping. Not only would the cyclic pitch be effected but the increased downflow would look like a climb condition--which requires more power to the rotors. This represents a decrease in ground effect. Around a ship, these airflow changes will generally come on suddenly during a takeoff or landing. Additionally, if the aircraft was low enough it would be subjected to a pitching moment, because the freeboard of the ship acts in effect as a step ground plane; see Figure 4.1.

B. SHIP MOTION CONSIDERATIONS

The ship motion parameters that affect recovery are pitch, roll, heave, surge, sway, and yaw. Of these, available literature indicates that the motions that contribute critically to the landing problem are heave and roll. It has been determined that the flight

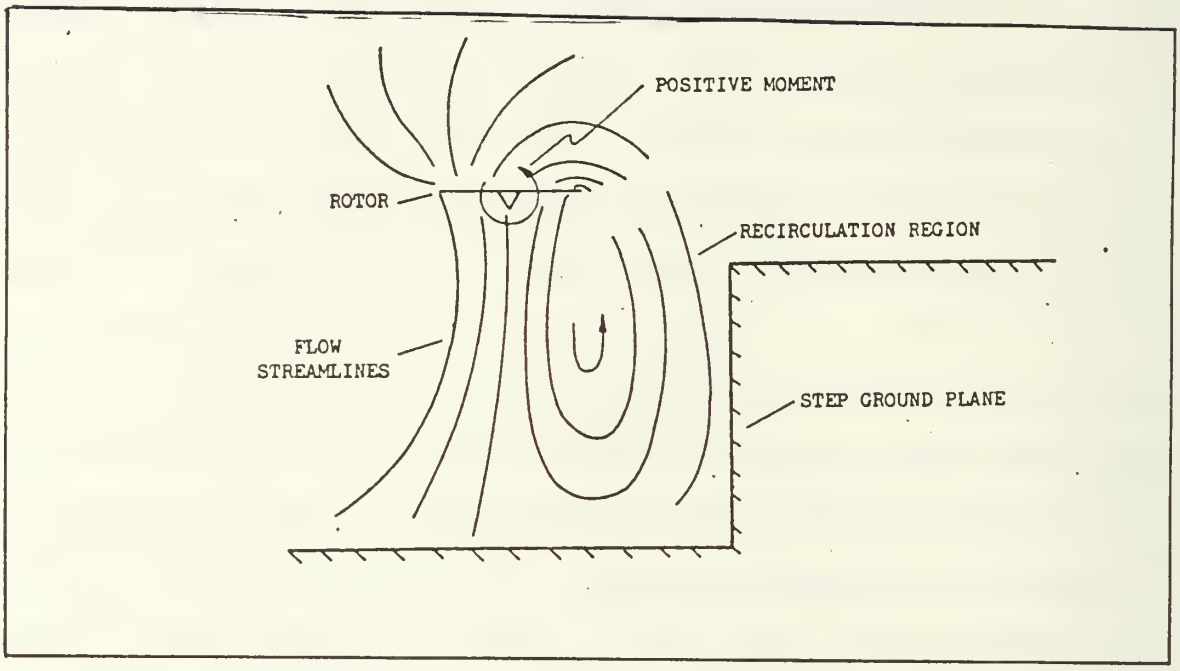

Figure 4.1

Qualitative Sketch of the Flow Field at

Position of Maximum Moment

characteristics of the QH-5Ø have made feasible the possibility of heave motion tracking, leaving the major difficulty of dealing with roll in high sea states to be solved.

Reference 3 develops a ship roll predictor that indicates a let-down sequence and provides an output signal proportional to the time-to-go until the desired touchdown time. The time estimates are used to control the descent

rate via collective control inputs. In this scheme, a landing sequence is initiated with the helicopter in a hover. It begins its let-down so as to reach the flare altitude two seconds prior to the desired touchdown time. The last two seconds allows the closing rate between the helicopter and ship to be reduced exponentially as the aircraft flares for a landing.

Reference 3 also considered the efforts that had previously been done to use a cable winch landing assist device. The study indicated that ship roll motion experienced in rough seas occurs at a magnitude and frequency such that the QH-5Ø could not keep up with the corresponding lateral movement. Peak QH-5Ø roll angles over nine degrees would be required in sea state 5. At very low altitudes, such peak roll magnitudes, with concomitant rates, are deemed intolerable.

C. AUTOMATIC LET-DOWN

1. Collective Pitch System

The implementation of the automatic let-down scheme delineated in Reference 3 would be subject to improvements in horizontal position control. Beyond use of a cable device, the only means apparently available that has the necessary accuracy is an optical tracking/ranging device developed as one component of the HYbrid Terminal Assist Landing (HYTAL) system; this device has the ability to give

positional accuracies of plus or minus a few feet. The automatic let-down technique gives promise of providing for successful recovery of the QH-5Ø in high sea states. The optical tracker/ranger of the HYTAL system, shown schematically in Figure 4.2, has the necessary precision to position a hovering QH-5Ø directly above the intended point of landing.

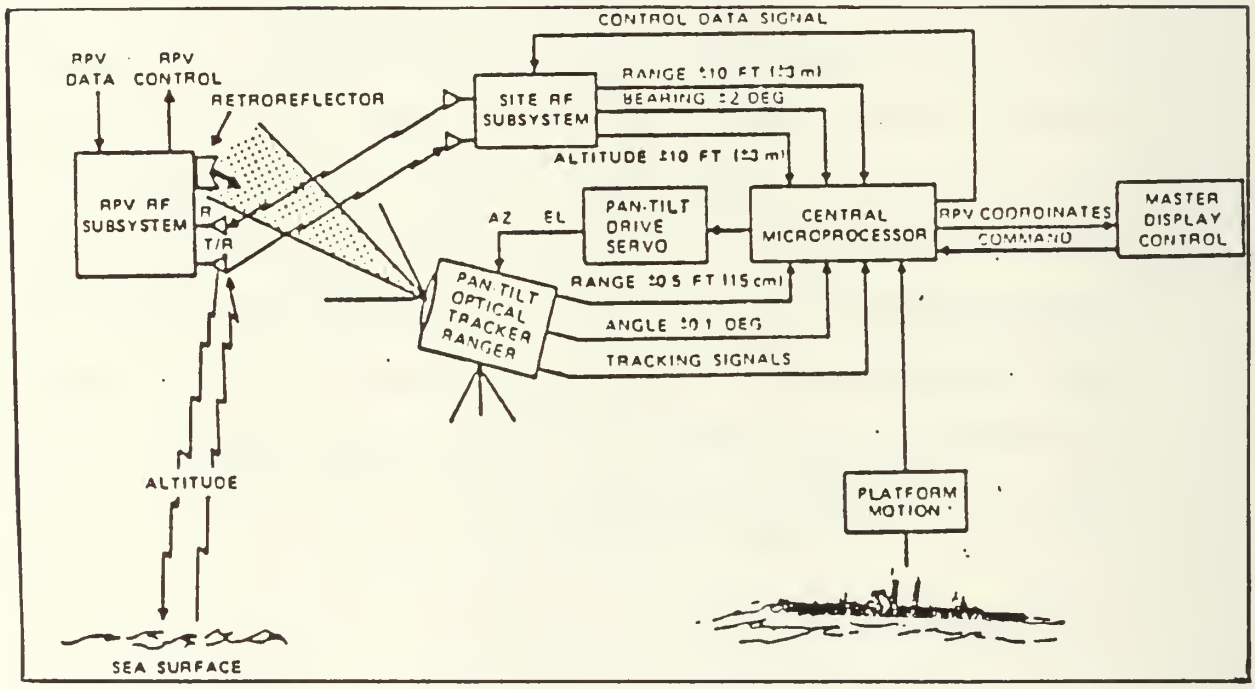

Figure 4.2

HYTAL Control Scheme

This technique envisions commencing a final descent to touchdown from a standby position hovering approximately 4Ø to 5Ø feet above the landing platform. It was concluded that it would be impractical to actually measure the waves in front of the ship because of the need for a wave motion

sensor, and the inability to project for enough into the future (approximately 10 seconds), to permit the QH 50 to commence its let-down so as to touchdown when roll angle is zero. This approach was discarded in favor of one that modeled the ship's motion, then operated essentially at an accelerated time scale, effectively projecting the ship's behavior into the future. Previous studies of ships' motion indicated that the two motions of heave and roll were the most important, and that the others could be ignored.

The roll motion was then simulated as a second-order model. A model of heave motion was not deemed possible, so the technique requires the QH-50 to track the vertical motion of the ship. This requires that the descent rate be very carefully controlled by collective control inputs, so that the QH-50 touches down at a nominal rate of 2.4 feet per second.

Of fundamental import in achieving this heave-motion tracking is the response time of the collective pitch system. Prouty [Ref. 6] indicates that helicopters react remarkably fast to control inputs. Figure 4.3 shows the collective analytical block diagram for the QH-50. This diagram depicts part of the automatic stabilization and control system designed to stabilize the RPV; it also accepts maneuver commands from the remote controller. It must be noted that the altitude reference used in this diagram is taken to be a radar altimeter; radar altimeters

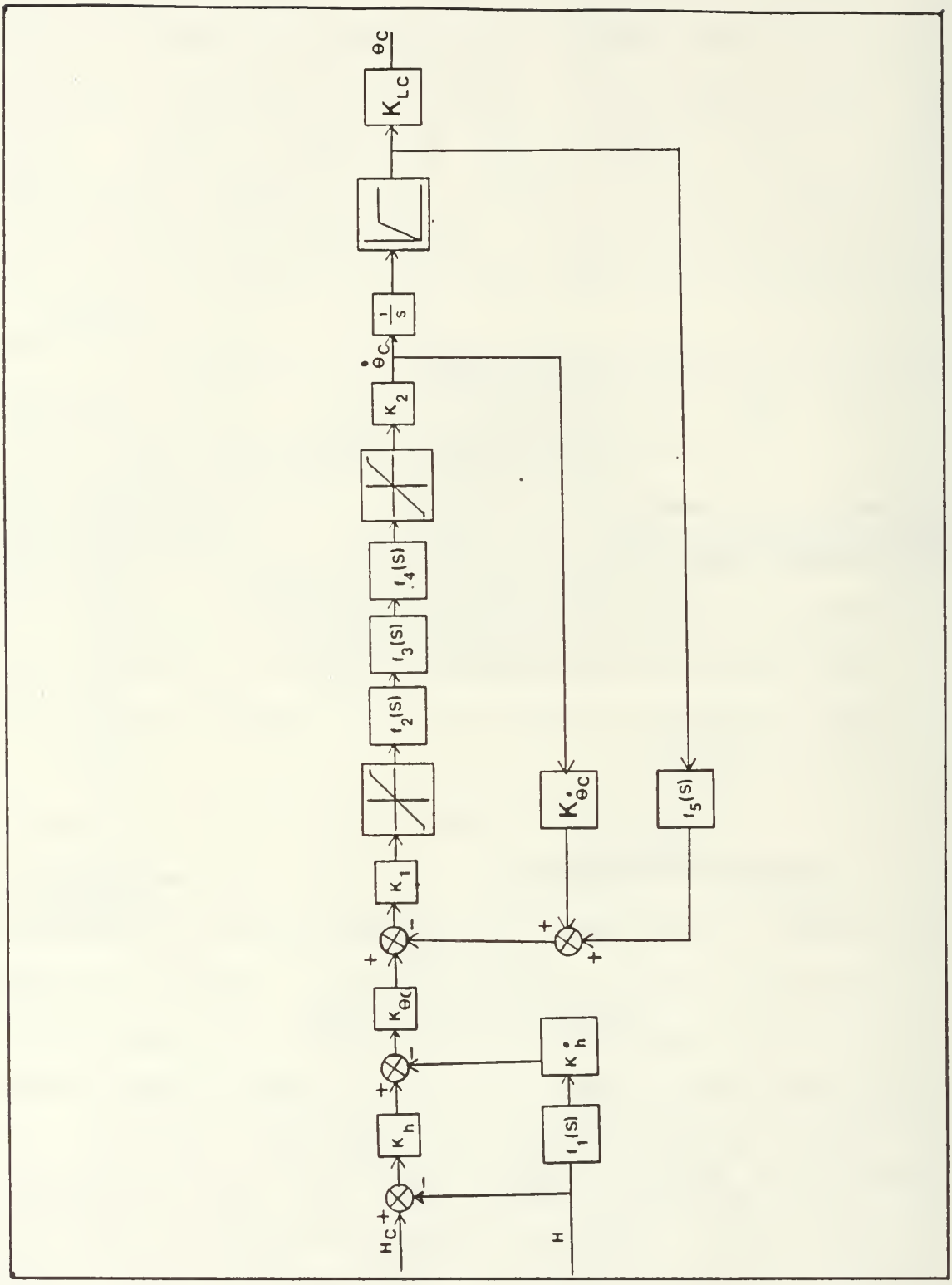

Figure 4.3 Collective Analytical Block Diagram

are not currently installed on the QH-5Ø. Values of the parameters of the individual blocks are given in Table II. The value of the first limiter is + 4Ø; the value of the second limiter is + 12ØØØ; the value of the third limiter is taken to be Ø to +2Ø.

The time response of this collective pitch system was simulated on the computer; the code is given in Appendix B. With the initial altitude arbitrarily set to zero, a commanded altitude of fifty feet was input. Figure 4.4 shows that the blade angle increases to four degrees in approximately Ø.7 seconds; Figure 4.5 shows the phase-plane diagram for the collective pitch change.

This appears to be a rather rapid response; however, it does not directly show how long it takes for the QH-5Ø to actually begin a climb from hover once commanded. Reference 3 states that the collective axis dynamic is such that there is a lag of 4.7 seconds between collective displacement and altitude rate response; this reference also suggests a modification to the existing AFCS to increase the system gain and thereby appreciably improve this characteristic. With this characteristic, the assumption remains that heave-tracking is possible.

2. Automatic Let-down Scheme

The roll predictor model used is a representation of the equation

TABLE II

COLLECTIVE ANALYTICAL BLOCK DIAGRAM PARAMETERS

Parameter	Value
$f_1(S)$	$\frac{\emptyset.22}{(\emptyset.22S + 1)(\emptyset.\emptyset127S + 1)}$
$f_2(S)$	$\frac{1}{(\emptyset.22S + 1)}$
$f_3(S)$	$\frac{\emptyset.3343(\emptyset.177S + 1)(\emptyset.\emptyset\emptyset64S + 1)}{\left[\left(\frac{S}{12\emptyset\Pi}\right)^2 + \frac{\emptyset.6S}{12\emptyset\Pi} + 1\right](\emptyset.2274S + 1)(\emptyset.\emptyset2274S + 1)}$
$f_4(S)$	$\frac{2513.16}{5.316S + 1}$
$f_5(S)$	$\frac{13.5S}{(13.5S + 1)(\emptyset.\emptyset1\emptyset6S + 1)}$
K_h	2.Ø2
K_m	3.875
K_{oc}	Ø.Ø75
K_{oc}	Ø.Ø5836
K_1	24.64
K_2	Ø.Ø15
K_{ic}	Ø.2Ø4

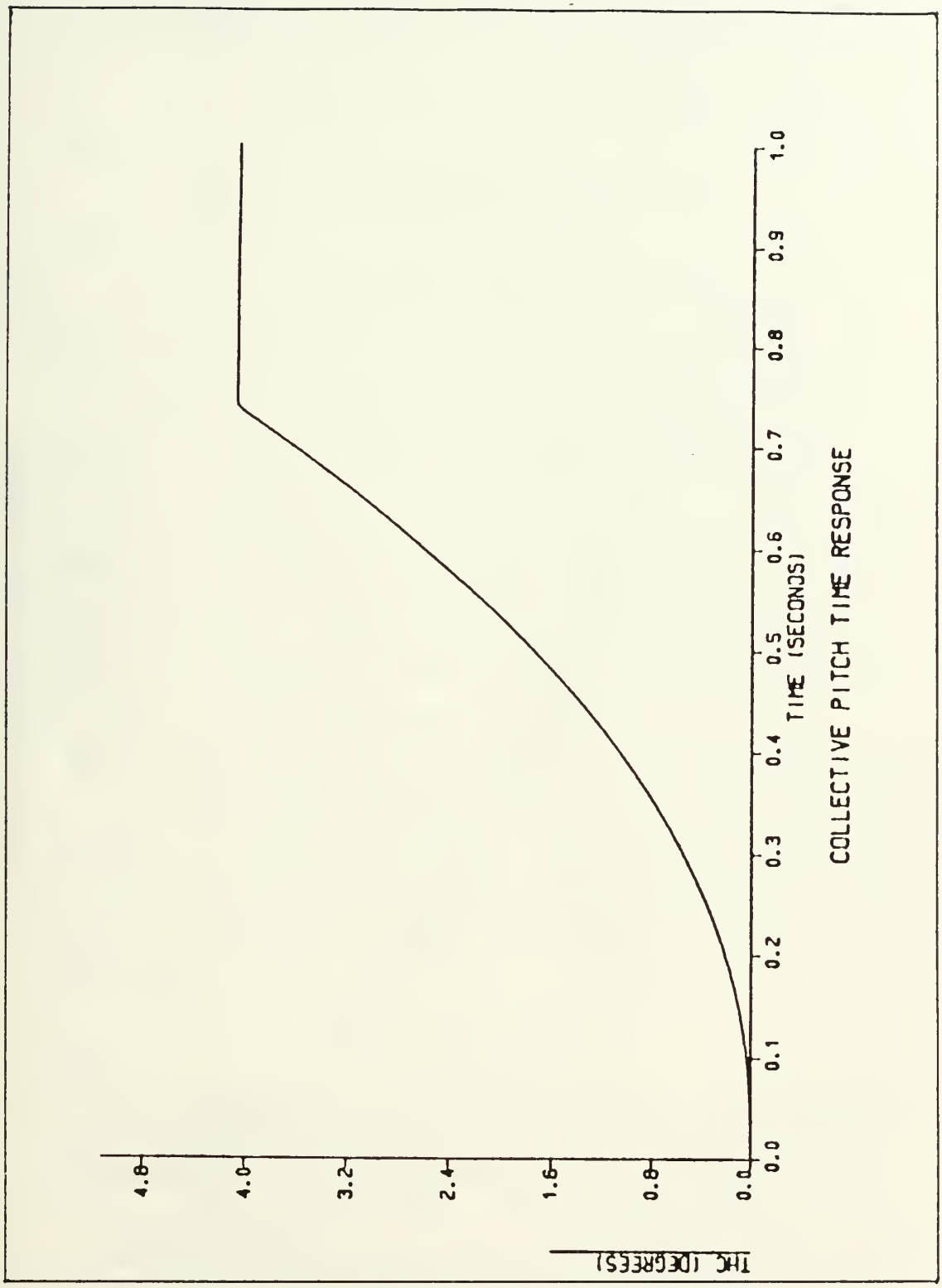

Figure 4.4 Collective Pitch Time Response

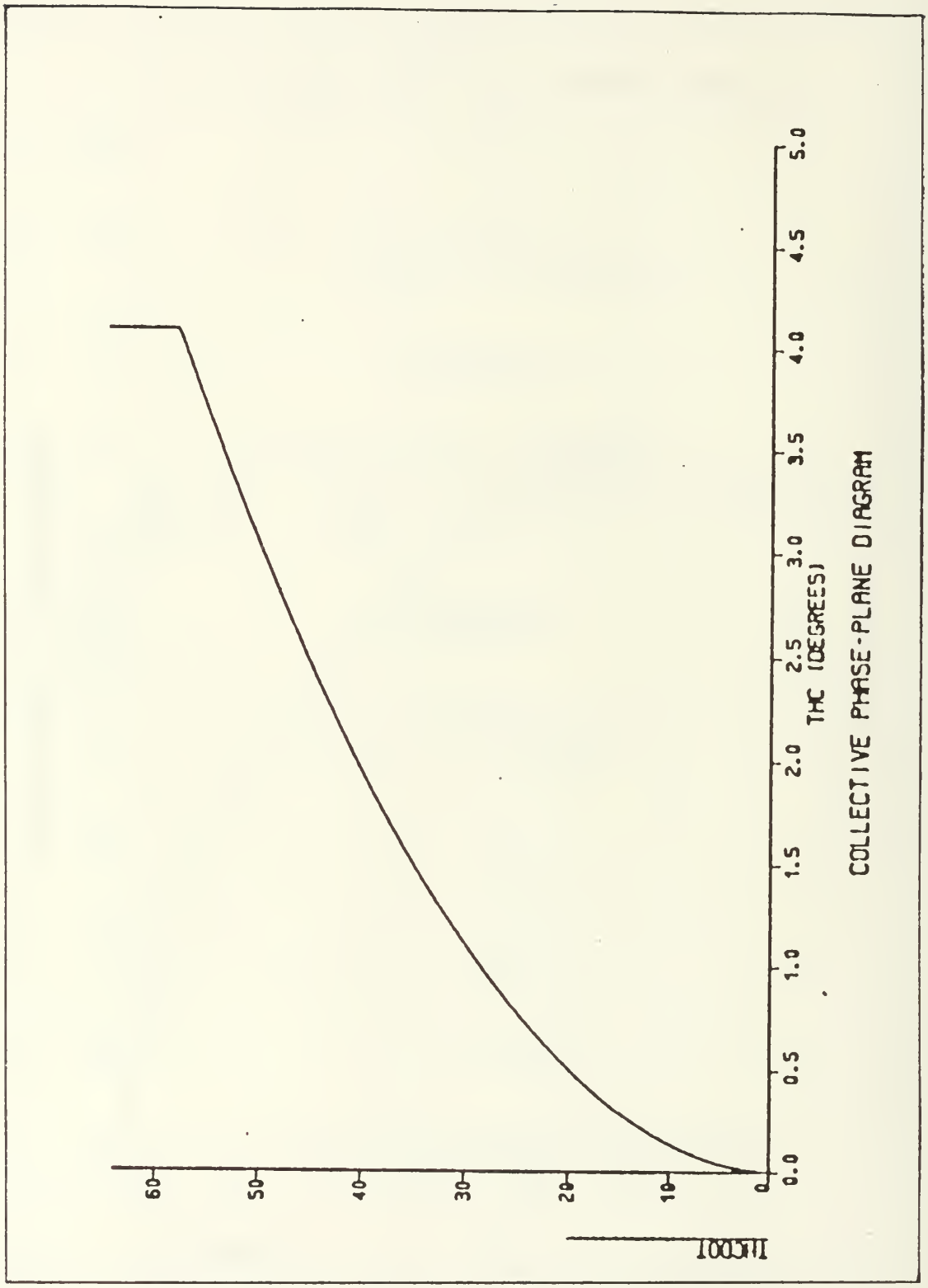

Figure 4.5 Collective Pitch Phase-plane Diagram

$$\frac{d^2\Phi}{dt} + 2\xi\omega_n\frac{d\Phi}{dt} + \omega_n^2\Phi = \emptyset$$

the solution to which is

$$\Phi(t) = A \exp\{-\xi\omega_n t\} \sin(\omega t + \Psi)$$

where ξ and ω_n are predetermined constants and A and Ψ are determined from the initial values for Φ and $d\Phi/dt$.

This predictor model is used to initiate a let-down so that eight seconds later the QH-5Ø touches down. The let-down is checked at 4 seconds and 2 seconds, with an automatic abort sequence if prescribed limits are exceeded. The descent rate is controlled via the collective axis, and includes a flare mode so that the QH-5Ø is descending at no more than 2.4 feet per second at touchdown.

This technique assumes perfect horizontal positioning, which would be quite difficult for an operator to achieve manually in the presence of the unsteady around a ship. The automatic let-down scheme is based on the following assumptions:

- direct control of the QH-5Ø collective pitch system is quick enough to enable the QH-5Ø to follow the ship's heave motion, obviating the need for a heave motion predictor
- hover site position is maintained automatically in spite of crosswinds and other external forces; that is to say, lateral and longitudinal control power and sensitivity of the QH-5Ø are adequate compared to ship roll accelerations.

* the above assumption requires automating control in the pitch and roll cyclic axes, thereby making the landing fully automatic

* descent from hover can be made after a prediction as to when the roll angle of the ship will be zero

* ship motion prediction is needed for roll only; ship pitch, surge, sway, and yaw are ignored (available literature indicates that these motions do not contribute significantly to the helicopter landing problem)

* the QH-5Ø would have an altitude control loop (built around an acceleration sensor and a radar altimeter), which could be integrated to provide an altitude rate and altitude displacement signal (the currently installed barometric referenced system senses disturbances other than local atmospheric pressure about the coaxial system caused by the whirling blades)

* the influence of ship's airwake effects (e.g., airflow disturbances from the ship's superstructure) does not unduly affect the altitude control in the let-down phase

The ship motion predictor will be used to predict the time when ship roll attitude will be zero and to provide a continuous update of the time during descent. Descent is initiated when the predicted zero-crossing time is at +8 seconds. The RPV is assumed to have the ability to track ship heave motion. Vertical rate command computations based on predictor information permit touchdown equally well at any point of the heave cycle; the descent rate is automatically controlled via collective control inputs.

Figure 4.6 shows the control system configured for automatic control of the QH-5Ø during recovery. [Ref. 3].

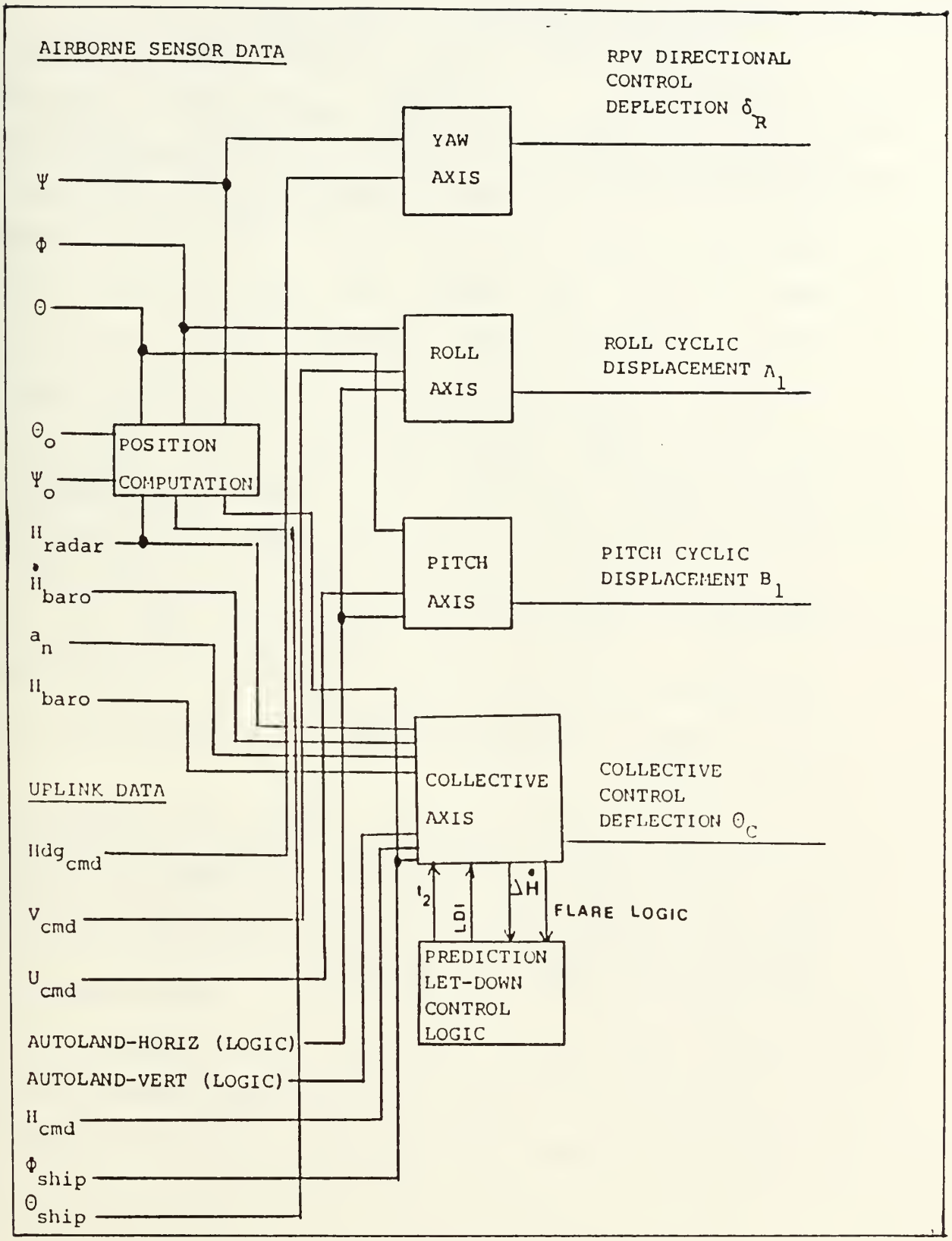

Figure 4.6 QH-5Ø HYTAL Control System

3. Let-down Control Law

The development of the let-down control law is found in Reference 7. In essence, the ship's roll motion predictor is used to initiate a let-down sequence while providing an output signal proportional to the time-to-go until the desired touchdown time. This time estimate is used to control the descent rate via collective control inputs. There are three different modes in the let-down sequence. In the standby mode, the helicopter is hovering at a fixed height above the deck (40-50 feet). In the let-down mode, the descent rate is continuously adjusted to cause the helicopter to arrive at flare altitude two seconds prior to the desired touchdown time. In the flare mode, the helicopter closing rate with the ship is reduced exponentially to arrive at the deck with a rate of descent of 2.4 feet per second and elapsed time approximately equal to two seconds.

The control law for the standby mode consists merely of a differential altitude rate (h) command proportional to the error between observed altitude (above the deck) and the reference altitude (e.g., 50 feet).

The let-down mode is designed to cause the RPV to arrive at nominal flare altitude two seconds prior to the desired touchdown time. To do so, the altitude rate command is adjusted to equal the ratio of altitude change required to the time remaining, i.e.,

$$\dot{\Delta h}_{cmd} = H - H_{fl} / -(t_2 - 2)$$

where H_{fl} = flare altitude, and t_2 = desired time of touchdown. This is the relationship which would have to be implemented and used as a sink rate command during the let-down mode. [Ref. 3]

The exponential flare law defines flare altitude to be a function of altitude rate:

$$h_{fl} = f(\dot{\Delta h})$$

The final two seconds (approximately) prior to touchdown are used to smoothly reduce the RPV sink rate from the constant value of the let-down mode to a lesser value suitable for touchdown impact. Since there is a lag between h command and h response, a time history for altitude is needed from which the time occupied by the maneuver can be computed as a function of initial flare sink rate flare entry. [Ref. 3]

Since sink rate during let-down is a function of let-down initiation altitude and flare altitude, a variationin flare entry sink rate in the let-down mode affects the flare time and therefore the touchdown time.

V. SURVEY OF HYTAL CONTROL ALGORITHMS

A. BACKGROUND OF HYTAL CONTROL ALGORITHMS

The HYbrid Terminal Assist Landing (HYTAL) system has been suggested as a system that would allow full automating of QH-50 recoveries aboard ships at sea [Ref. 9]. The design of this system is documented in Reference 4, which cites the fact that the two components of the HYTAL system have been successfully tested independently. The optical component, which functions as a tracker/ranger, appears to have the precision necessary to fully control a QH-50 during ship recovery up to sea state 5, during which waves of up to 13 feet [Ref. 9] and winds up to 30 knots [Ref. 10] are encountered.

Reference develops control algorithms and discrete observers for closed loop control of the RPV flight path using the HYTAL system. Implementation of digital control could be used to improve the flight control capability of the QH-50.

If discrete measurements of position are taken using the tracker/ranger, the discrete Kalman filter can be used; discrete measurements arise when a system is sampled as part of a digital control scheme [Ref. 11]. For modern control applications, the discrete Kalman filter is usually used.

This technology is straightforward and compatible with present control methods.

B. RESPONSE OF COUPLED LONGITUDINAL MODEL

Reference synthesizes pitch, roll and vertical controllers based upon state variable models derived from dynamics of the airframe at hover, onboard analog loops and actuators. The airframe models are based on stability derivatives obtained from Reference 3. A full-system, coupled, longitudinal 9th-order model of the aircraft at 20 knots is derived, and is shown in Figure 5.1. The time response of this system was investigated using the Interactive Ordinary Differential Equations (IODE) program. Starting from a reference point of zero, a climb to 500 feet and transit to 5000 feet was commanded. The results are shown in Figures 5.2 through 5.8.

Figure 5.2 shows the time response of longitudinal position and velocity. Although the response settles on the commanded distance, there is a very large overshoot. Also, the settling time is less than 15 seconds; clearly, if the QH-50 could transit 5000 feet in less than 15 seconds, the airframe aerodynamics would be exceeded. Looking at the speed, U, it can be seen that the peak value of approximately 1500 feet per second, attained in approximately 2 seconds, would also exceed the performance limits of the QH-50.

FULL-SYSTEM IODE EQUATIONS

$$\begin{bmatrix} \dot{X} \\ \dot{U} \\ \dot{H} \\ \dot{W} \\ \dot{Q} \\ \dot{\theta} \\ \dot{\theta}_{f_\theta} \\ \dot{B} \\ \dot{\theta}_c \end{bmatrix} = \begin{bmatrix} 0 & 1.0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & -0.052 & 0 & 0 & 2.22 & -32.2 & 0 & 57.5 & 8.59 \\ 0 & 0 & 0 & -1.0 & 0 & 34.0 & 0 & 0 & 0 \\ 0 & -0.34 & 0 & -0.563 & 34.0 & 0 & 0 & 25.0 & -409.0 \\ 0 & 0.0319 & 0 & -0.00455 & -1.59 & 0 & 0 & -40.9 & 1.48 \\ 0 & 0 & 0 & 0 & 1.0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 34.5 & 181.0 & -12.5 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 4.91 & -46.3 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -47.0 \end{bmatrix}$$

$$\begin{bmatrix} X \\ U \\ H \\ W \\ Q \\ \theta \\ \theta_{f_\theta} \\ B \\ \theta_c \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \\ 10.5 & 0 \\ 0 & 4.64 \end{bmatrix} \begin{bmatrix} V_{\delta_r} \\ V_c \end{bmatrix}$$

$V_r = -0.104\ (X - X_c) - 0.205U$

$V_c = -0.191\ (H - H_c) - 0.0864H - 2.940$

Figure 5.1 HYTAL Coupled Longitudinal Model

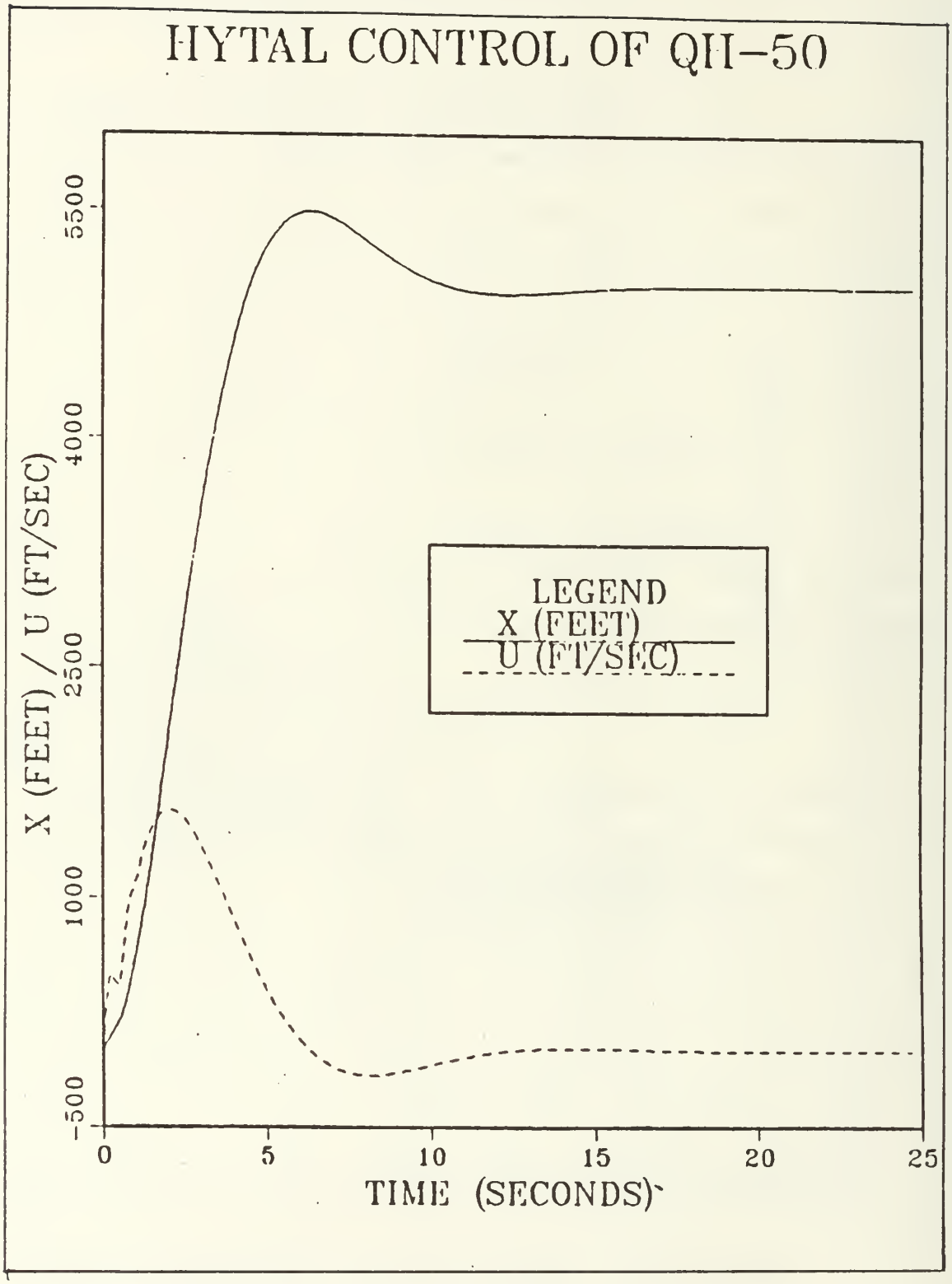

Figure 5.2 Distance/Velocity Response

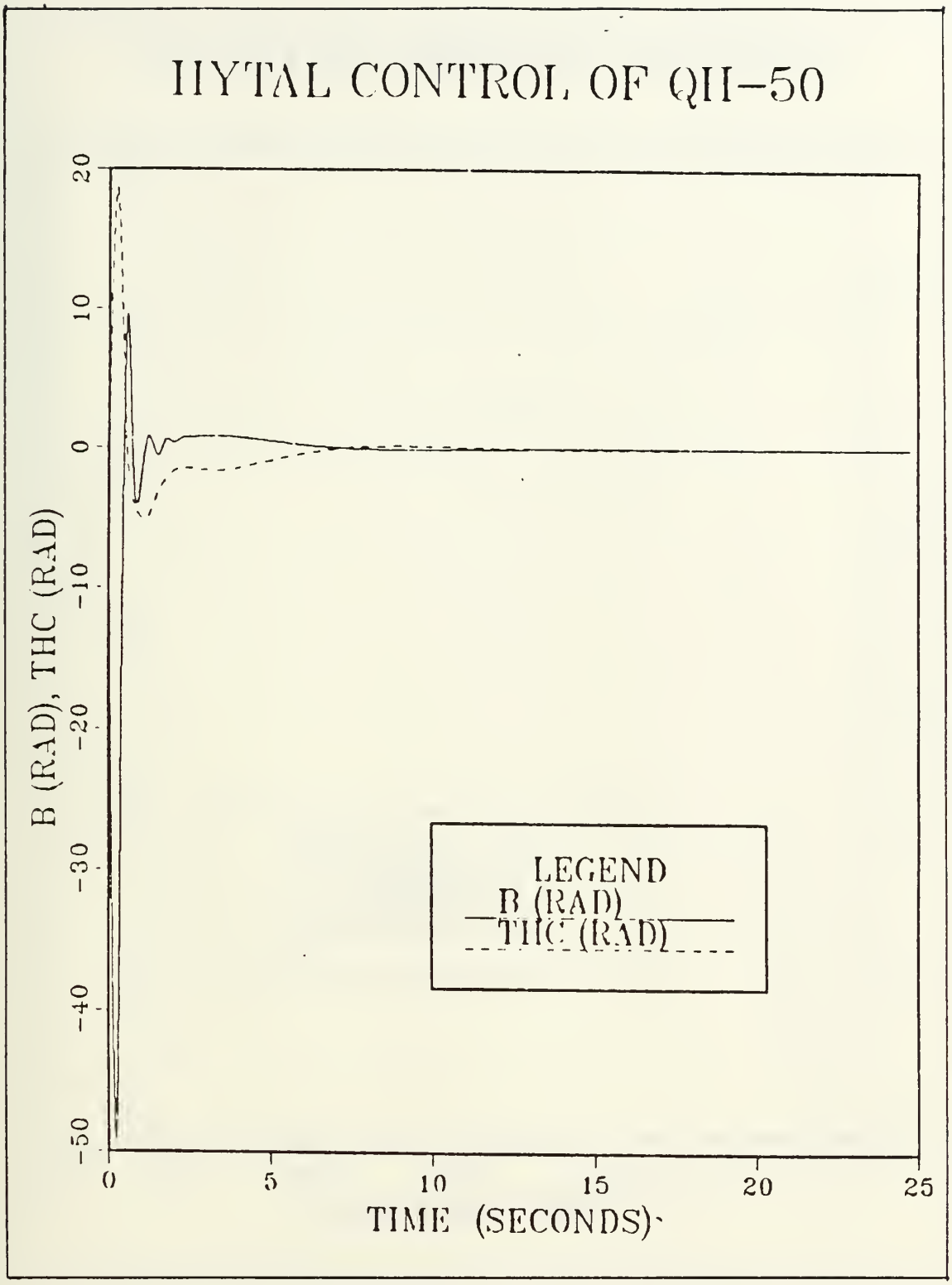

Figure 5.3 HYTAL Collective Response

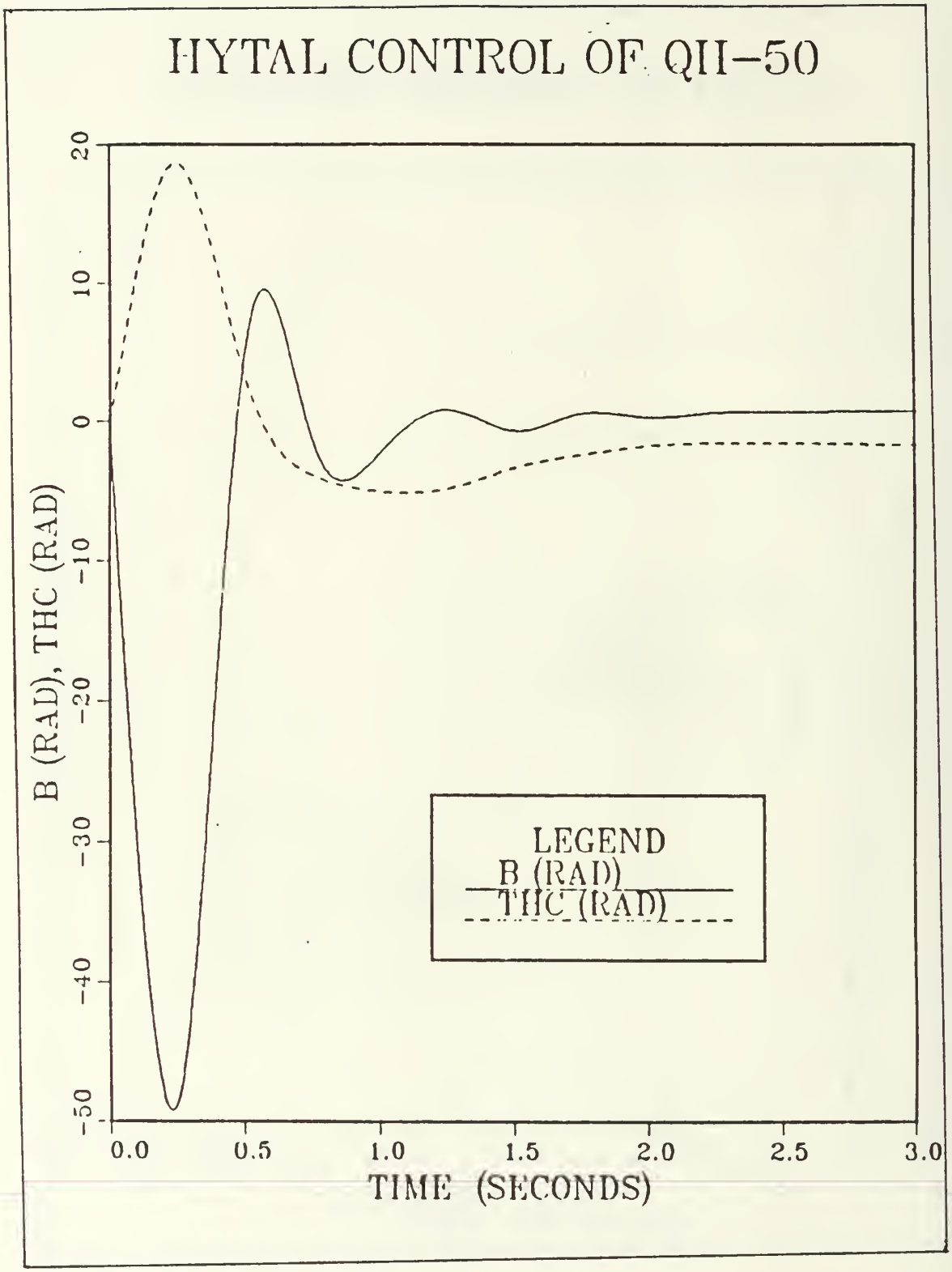

Figure 5.4 HYTAL Collective Response (Expanded Scale)

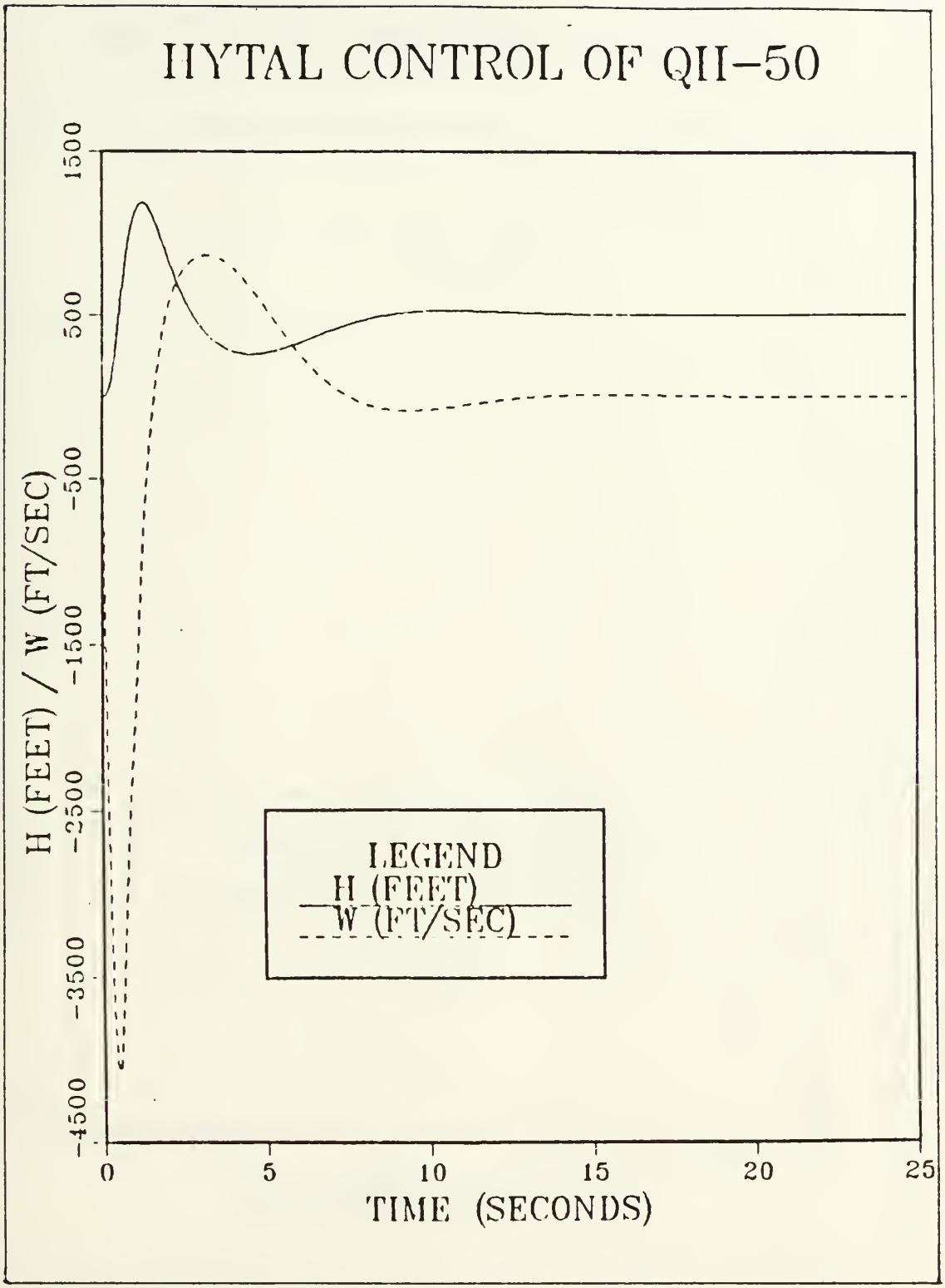

Figure 5.5 HYTAL Altitude/Vertical Velocity Response

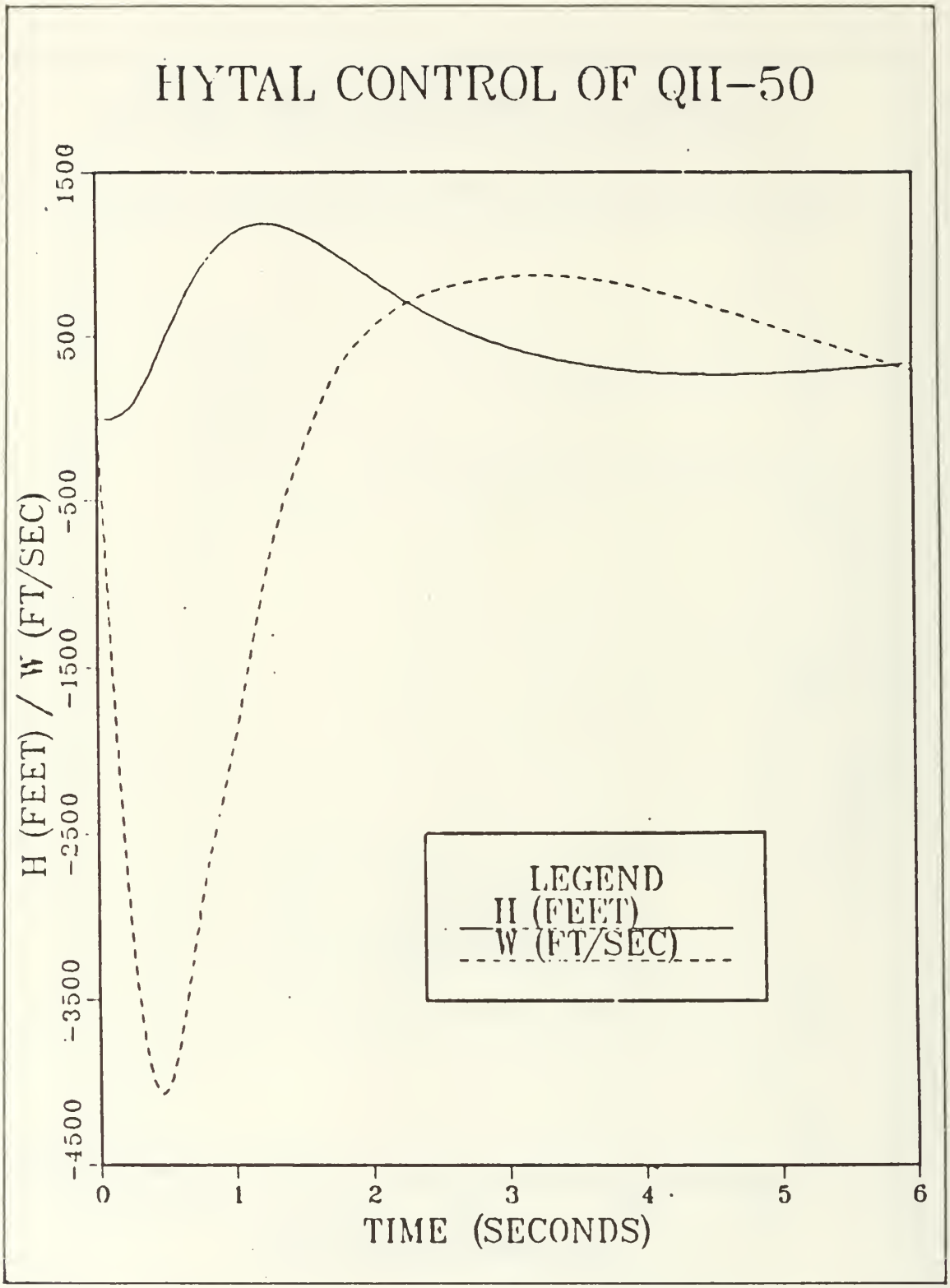

Figure 5.6 HYTAL Altitude/Vertical Velocity Response (Expanded Scale)

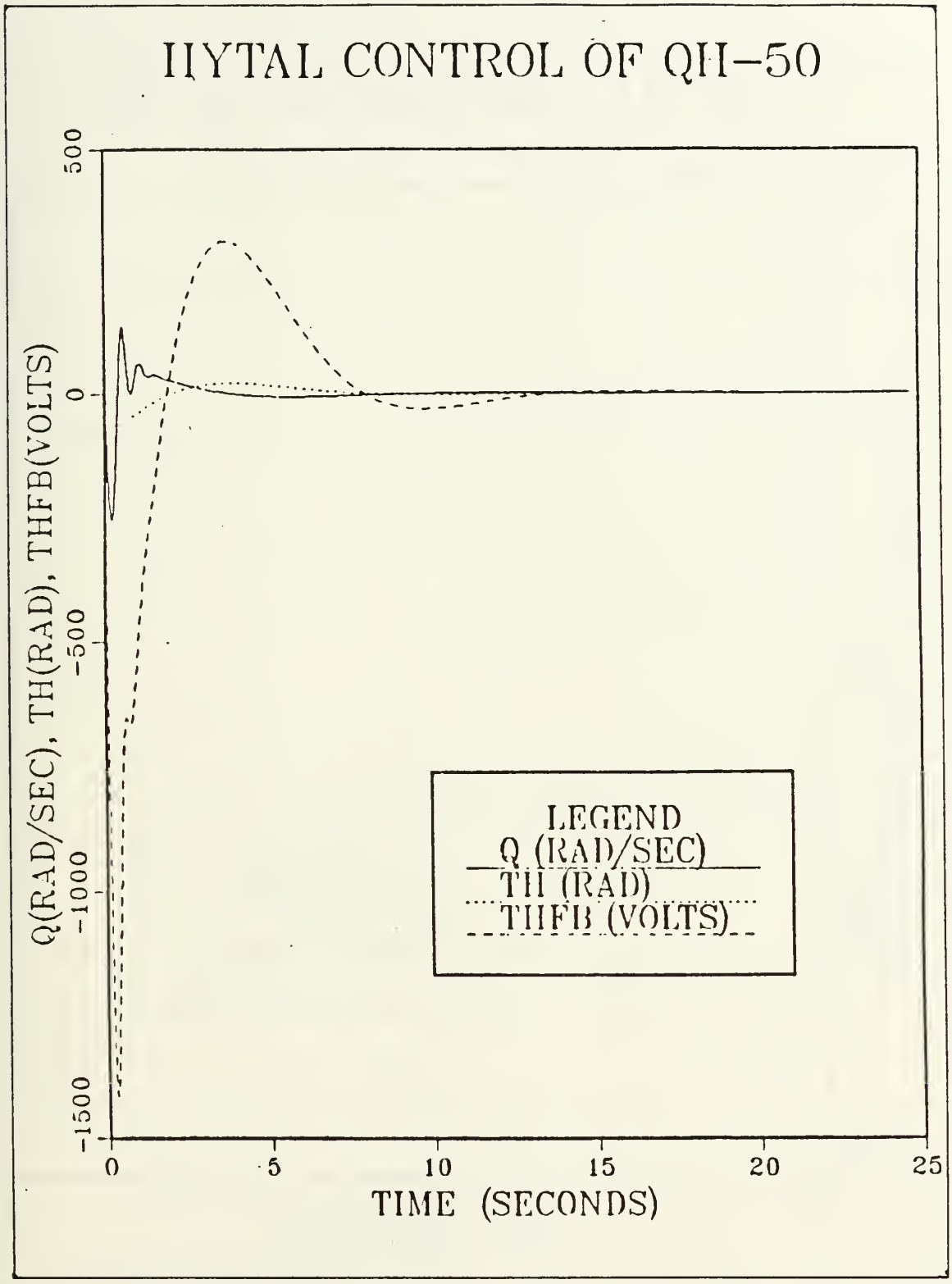

Figure 5.7 HYTAL Pitch Response

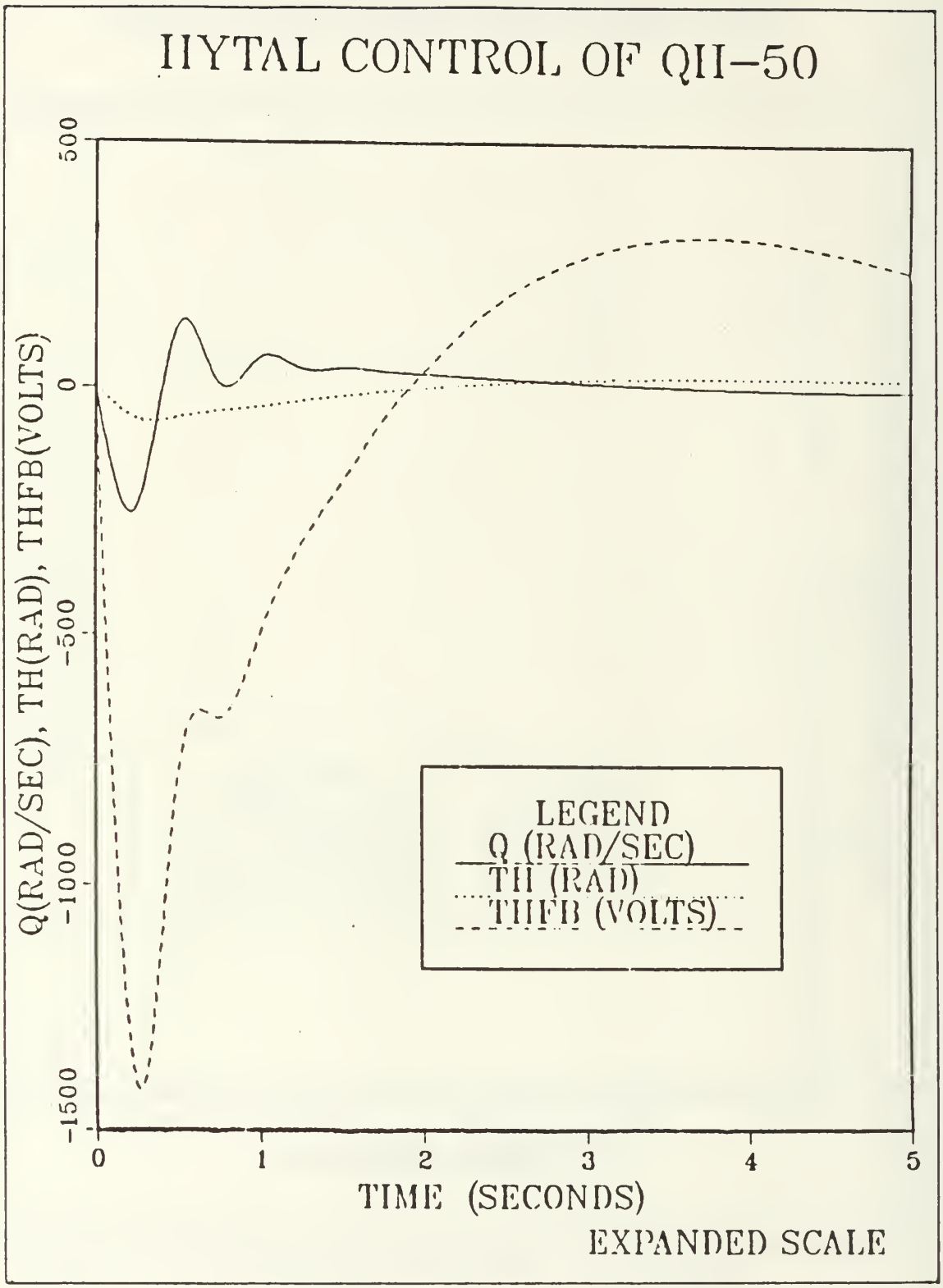

Figure 5.8 HYTAL Pitch Response (Expanded Scale)

Figure 5.3, which is shown in expanded time scale in Figure 5.4, shows the time response of longitudinal cyclic pitch, B, and collective. The very large transients for each --close to 50 radians of longitudinal cyclic pitch and 10 radians of collective pitch--are unrealistic, although these large values appear to qualitatively coincide with the responses of the longitudinal distance and velocity shown in Figure 5.2.

Figure 5.5, shown with an expanded time scale in Figure 5.6, shows similar, unrealistic transients for altitude, H, and vertical velocity, W. Both steady-state values appear to be as expected, but the inordinately fast settling times clearly are not possible.

Finally, Figure 5.6, shown with an expanded time scale in Figure 5.7, shows large transient responses in pitch, Q; pitch angle; and pitch attitude loop feedback voltage.

It must be noted that although the final steady-state responses of this coupled system are what was expected, the compressed time scale and large transients are apparently unrealistic; such behavior in an actual QH-50 would be beyond aerodynamic and performance limits.

C. CONTROL SYSTEM HANDOFF

Reference 3 reiterates the fact that there is a transition point in the control of the QH-50 between the

cruise and maneuver modes. It is suggested that this handoff be made to coincide with the shift between the RF and electro-optical components of the HYTAL system. To preclude undesirable transitions of the QH-50 while shifting from mode to mode, it would be necessary to intitialize the system being handed-off to to the values of heading, altitude and airspeed of the system being handed-off from.

VI. CONCLUSIONS

The survey of this conceptual examination of the QH-50 DASH system has led to the following conclusions:

1. Means of achieving safe recovery of the QH-50 RPV in adverse conditions up to and including sea state 5 is apparently feasible with the advent of the HYTAL control system.

2. The means consist of providing automatic let-down control via collective pitch channel, utilizing a prediction of ship roll motion to permit touching down on a nearly level deck.

3. The potentially troublesome effect of ship heave motion is eliminated by causing the RPV to track the vertical motion of the landing platform during the let-down. By automating the vertical axis, precise control of touchdown sink rate and touchdown time (with respect to ship roll motion) can be achieved.

4. It appears feasible to fully automate the horizontal position control by coupling the information provided by the HYTAL tracker/ranger on the ship to the QH-50 cyclic axes flight control system while underway on ship's heading. Any serious effort to update the QH-50 DASH system into a platform for operational service would require perfecting this control system at a minimum.

5. A suggested equipment package for total modernization would include a vertical acceleration sensor, radar altimeter, or three-axis rate gyros, and an interface unit to make it all compatible with the HYTAL system.

6. Sensor packages (e.g., TV camera, ECM/ECM gear) would be dependent upon the type of mission tasking employed.

7. For the QH-50 system as it currently exists, possible missions include being used as an expendable decoy for anti-ship missile defense tasks.

VII. RECOMMENDATIONS

A. GENERAL

As the march of science and technology (e.g., ASROC and LAMPS ASW helicopters) over-ran the QH-5Ø and cast it along the wayside, so may further progress in RPV control systems provide the means for a new lease on life for the QH-5Ø. With the successful testing of the independent elements of the HYTAL system, the time may be at hand to bring the QH-5Ø back into operational serviceability. The next step would be to configure a refurbished QH-5Ø for flight testing of the full system.

B. SPECIFIC

The following specific recommendations are included for consideration:

1. The HYTAL control algorithms developed in Reference should be implemented.
2. A refurbished QH-5Ø should be fitted with a radar altimeter, vertical acceleration sensor, and other equipment needed under the HYTAL concept.
3. A land-based trial of the system should be investigated.
4. Determine the QH-5Ø's remaining useful life and the operational and financial resources required to endow these RPV's with an operational viability and survivability commensurate with the challenges and demands of identified mission tasking.
5. Determine the actual cost of refurbishing the QH-5Ø.
6. Determine whether the operational utility of such a conversion justifies the cost of the conversion.

APPENDIX A

SIMPLIFIED MODEL BASED ON EQUATIONS OF MOTION

```
TITLE DASH EQUATIONS OF MOTION
CONST GRAV=32.174, PI=3.1415960
CONS IXX = 150.0, IYY = 220.0, IZZ = 220.0, MASS = 40.0
* MEASURED LB FT SEC**2                          SLUGS
*
*****************************************************************
*   UNITS                                                       *
*                                                               *
*   MOMENTS OF INERTIA   IXX,IYY,IZZ          LB-FT-SEC**2      *
*   FORCES               FATX,FATY,FATZ       LB                *
*   MOMENTS              LAT,MAT,NAT          LB-FT             *
*   ANGLES               PSI,THT,PHI          RADIANS           *
*                        PSIDEG,THTDEG,PHIDEG DEGREES           *
*   ANGLE RATES             P   ,   Q   ,   R  RAD/SEC           *
*                        (PITCH),(ROLL),(YAW                    *
*   VELOCITIES           UU,VV,WW,UERTH,ET*C  FT/SEC            *
*                        WR                   RAD/SEC           *
*                                                               *
*****************************************************************
*
FIXED FM
ARRAY TRANS(3)
*
INITIAL
*
***  CONVERSIONS
*
***  MOMENTS OF INERTIA
*
      IYMIZ = IYY - IZZ
      IZMIX = IZZ - IXX
      IXMIY = IXX - IYY
*
*** INITIAL CONDITIONS
*
       PO   = 0.
       QO   = 0.
       RO   = 0.
       UO   = 0.
       VO   = 0.
       WO   = 0.
       PHIO = 0.
       THTO = 0.
```

```
        PSIC = Ø.
        WRO  = WRPMØ*2.PI/6Ø.
        ALTO = Ø.
*
DYNAMIC
*
*** INPUT CALCULATIONS
*
      ENDT = STRT + DUR
      IF (FM.EQ.1) THEN
           FX = X*(STEP(STRT)-STEP(ENDT))
           FY = Y*(STEP(STRT)-STEP(ENDT))
           FZ = Z*(STEP(STRT)-STEP(ENDT))
           L  = Ø.
           M  = Ø.
           N  = Ø.
      ELSEIF (FM.EQ.2) THEN
           L  = X*(STEP(STRT)-STEP(ENDT))
           M  = Y*(STEP(STRT)-STEP(ENDT))
           N  = Z*(STEP(STRT)-STEP(ENDT))
           FX = Ø.
           FY = Ø.
           FZ = Ø.
      ELSEIF (FM.EQ.Ø) THEN
           FX = Ø.
           FY = Ø.
           FZ = Ø.
           L  = Ø.
           M  = Ø.
           N  = Ø.
     END IF
*
***  COORDINATE TRANSLATION COMPONENTS
*****  BODY FIXED TO EARTH-FIXED (EHLER ANGLES)
*
   TRANS(1) = COS(PSI)*COS(THT)
   TRANS(2) = COS(PSI)*SIN(THT)*SIN(PHI) - SIN(PSI)*COS(PHI)
   TRANS(3) = COS(PSI)*SIN(THT)*COS(PHI) + SIN(PSI)*SIN(PHI)
*
   TRANS(4) = SIN(PSI)*COS(THT)
   TRANS(5) = SIN(PSI)*SIN(THT)*SIN(PHI) + COS(PSI)*COS(PHI)
   TRANS(6) = SIN(PSI)*SIN(THT)*COS(PHI) - SIN(PHI)*COS(PSI)
*
   TRANS(7) = -SIN(THT)
   TRANS(8) = COS(THT)*SIN(PHI)
   TRANS(9) = COS(THT)*COS(PHI)
*
***  FORCE COMPONENTS (SIMPLE MODEL)
*
     FAX = FX/2.
***  FTX SET FOR DASH HOVER
     FTX = FX/2.  - GX*MASS
```

```
*     FTX = FX/2.
      FAX = FX/2.
***   FTY SET FOR DASH HOVER
      FTY = FY/2. - GY*MASS
*     FTY = FY/2.
      FAY = FY/2.
***   FTZ SET FOR DASH HOVER
      FTZ = FZ/2. - GZ*MASS
*     FTZ = FZ/2.
      FATX = FAX + FTX
      FATY = FAY + FTY
      FATZ = FAZ + FTZ
*
***   MOMENT COMPONENTS (SIMPLE MODEL)
*
      LA = L/2.
      LT = L/2.
      MA = M/2.
      MT = M/2.
      NA = N/2.
      NT = N/2.
      LAT = LA + LT
      MAT = MA + MT
      NAT = NA + NT
*
***   GRAVITY COMPONENTS
*
      GX =  GRAV*TRANS(1)
      GY =  GRAV*TRANS(2)
      GZ =  GRAV*TRANS(3)
*
DERIVATIVE
*
***   MOMENT EQUATIONS
*
      PD   = (IYMIZ*R*Q + LAT)/IXX
      QD   = (IZMIX*P*R + MAT)/IYY
      RD   = (IXMIY*P*Q + NAT)/IZZ
*
***   FORCE EQUATIONS
*
      UD   = (VV*R - WW*Q) + FATX/MASS + GX
      VD   = (WW*P - UU*R) + FATY/MASS + GY
      WD   = (UU*Q - VV*P) + FATZ/MASS + GZ
*
***   ANGLE EQUATIONS
*
     PHID  = P + (Q*SIN(PHI) + R*COS(PHI))*TAN(THT)
     THTD  = Q*COS(PHI) - R*SIN(PHI)
     PSID  = (Q*SIN(PHI) + R*COS(PHI))/COS(THT)
*
*
```

```
*** VELOCITIES
*
***** DASH TOTAL VELOCITY (BODY FIXED)
      VTOT = SQRT(UU**2 + VV**2 + WW**2)
*
***** EARTH-FIXED VELOCITIES
*
      UERTH = UU*TRANS(1) + VV*TRANS(2) + WW*TRANS(3)
*
      VERTH = UU*TRANS(4) + VV*TRANS(5) + WW*TRANS(6)
*
      WERTH = UU*TRANS(7) + VV*TRANS(8) + WW*TRANS(9)
*
****** GROUND SPEED
      GRNSPD = SQRT(VERTH**2 + UERTH**2)
*
*
***INTEGRATIONS
*** MOMENT EQUATIONS
*
       P  =  INTGRL(PO,PD)
       Q  =  INTGRL(QO,QD)
       R  =  INTGRL(RO,RD)
*
***  FORCE EQUATIONS (VELOCITIES)
*
      UU  = INTGRL(UO,UD)
      VV  = INTGRL(VO,VD)
      WW  = INTGRL(WO,WD)
*
***  ANGLES
*
      PHI   = INTGRL(PHIO,PHID)
      THT   = INTGRL(THTO,THTD)
      PSI   = INTGRL(PSIO,PSID)
      PHIDEG = RADEG*PHI
      THTDEG = RADEG*THT
      PSIDEG = RADEG*PSI
*
***   ROTOR
*
      WR  = INTGRL(WRO,WRD)
      WRPM= WR*60./(2.*PI)
*
***   ALTITUDE
      ALT   = INTGRL(ALTO,UVERT)
*
*
CONTRL FINTM = 10, DELT = 0.01
PRINT .1, PHIDEG,THTDEG,PSIDEG,UU,VV,WW,WRPM
SAVE 0.01,PHIDEG,THTDEG,PSIDEG,UVERT,GRNSPD,WRP,UU,VV,WW,WRD
PARAM FM=0.,X-0.,Y-0.,Z-0.,WRPM0=610.,WRD=0.,STRT=0.,DUR=5.
```

```
LABEL (ALL) ZERO FORCES/MOMENTS
GRAPH(G1,DE=TEK618) TIME(NI=10,UN=SEC) PHIDEG(NI=10, ...
     UN=DEGREES,LO=-90,SC=90,LI=1)
GRAPH(G2,DE=TEK618) TIME(NI=10,UN=SEC) THTDEG(NI=10, ...
     UN=DEGREES,LO=-90,SC=90,LI=3)
GRAPH(G3,DE=TEK618) TIME(NI=10,UN=SEC) PSIDEG(NI=10, ...
     UN=DEGREES,LO=-90,SC=90,LI=3)
GRAPH(G4,DE=TEK618) TIME(NI=10,UN=SEC) UU(NI=0, ...
     UN='FEET/SEC',LO=-40,SC=10,LI=1)
GRAPH(G5,DE=TEK618) TIME(NI=10,UN=SEC) VV(NI=0, ...
     UN='FEET/SEC',LO= 40,SC=10,LI=3)
GRAPH(G6,DE=TEK618) TIME(NI=10,UN=SEC) WW(NI=0, ...
     UN='FEET/SEC',LO=-40,SC=10,LI=4)
GRAPH(G7,DE=TEK618) TIME(NI=10,UN=SEC) WDPM(NI=0,UN=RPM)
GRAPH(G8,DE=TEK618) TIME(NI=10,UN=SEC) WRD(NI=0,UN=' ...
     ROTOR ACCELERATION')
GRAPH(G9,DE=TEK618) TIME(NI=10,UN=SEC) UVERT(NI=10, ...
     LO=-10,SC=5,LI=1)
GRAPH(DE=TEK618) TIME(NI=10,UN=SEC) GRNSPD(NI=10, ...
     LO=-10,TI=0.8,UN='FEET/SEC',SC=5,LI=3)
END
PARAM FM=1,X=100.,Y=0.,Z=0.,SRPM0=610.,WRD=0.,STRT=0.,DUR=5.
CANCEL LABEL (ALL)
LABEL (ALL) FORCE IN X - 100 POUNDS
END
PARAM FM=1,X=0.,Y=100.,Z=0.,WRPM0=610.,WRD=0.,STRT=0.,DUR=5
CANCEL LABEL (ALL)
LABEL (ALL) FORCE IN Y - 100 POUNDS
END
PARAM FM=1,X=0.,Y=0.,Z=100.,WRPM0=610.,WRD=0.,STRT=0.,DUR=5
CANCEL LABEL (ALL)
LABEL (ALL) FORCE IN Z - 100 POUNDS
END
PARAM FM=0.,X=0.,Y=0.,Z=0.,WRPM0=610.,WRD=5.,STRT=0.,DUR=5.
CANCEL LABEL (ALL)
LABEL (ALL) WRD = 5
END
PARAM FM=2,X=100.,Y=0.,Z=0.,WRPM0=610.,WRD=0.,STRT=0.,DIR=5.
CANCEL LABLE (ALL)
END
STOP
```

APPENDIX B

COLLECTIVE ANALYTIC TIME RESPONSE

```
*************************************************************
*                                                           *
*   TIME RESPONSE OF THE QH-50, BASED ON THE COLLECTIVE     *
*                ANALYTIC BLOCK DIAGRAM                     *
*                ROBERT S. PACKULOVICH                      *
*                      APRIL 1987                           *
*                                                           *
*************************************************************
*                                                           *
*      THIS PROGRAM DETERMINES THE TIME RESPONSE OF THE     *
*      COLLECTIVE PITCH SYSTEM ON THE QH-50 HELICOPTER,     *
*            AND PLOTS THE ASSOCIATED GRAPH                 *
*                                                           *
*************************************************************
*
*
TITLE COLLECTIVE ANALYTIC
PARAM HC=5ØØ.Ø, KH=2.Ø2, KTHC=Ø.Ø75, K1=24.64, K2=Ø.Ø15, ...
      KLC=Ø.2Ø4, KTHDC=Ø.Ø5336, KHDOT=3.875
ARRAY A(3),B(5),C(2),D(3),E(2),F(3)
TABLE A(1)=Ø.ØØ11328, A(2)=Ø.1834, A(3)=1.Ø
TABLE B(1)=3.638469E-Ø8, B(2)=9.99ØØE-Ø6,B(3)=5.576E-Ø3, ...
      B(4)=Ø.2517315, B(5)=1.Ø
TABLE C(1)=13.5, C(2)=Ø.Ø
TABLE D(1)=13.5, C(2)=Ø.Ø
TABLE E(1)=Ø.22, D(2)=Ø.Ø
TABLE F(1)=Ø.ØØ2794, F(2)=Ø.2327, F(3)=1.Ø
INCON H=5Ø.Ø
DERIVATIVE
      THC = KLC * TH
      TH  = LIMIT(Ø.Ø,2Ø.,THCC)
      THCC = INTGRL(Ø.Ø,THCDOT)
      THCDOT = K2 * FF
      FF = LIMIT(-12ØØØ.Ø,12ØØØ.Ø,EE)
      EEE = REALPL(Ø.Ø,5.316,DD)
      EE  = 2513.16 * EEE
      DDD = TRNFR(2,4,Ø.Ø,A,B,CC)
      DD  = Ø.3343 * DDD
      CC  = REALPL(Ø.Ø,Ø.Ø22,BB)
      BB  = LIMIT(-4Ø.Ø,4Ø.Ø,AA)
      AA  = K1 * TACH
      TACH = HHCC - TACHA
      TACHA = KTHDOT + FTH
      KTHDOT = KTHDC * THCDOT
```

```
        PTH = TRNFR(1,2,Ø.Ø,C,D,TH)
        HHCC = KTHC * HHC
        HHC = KHE - HHE
        KHE = KH * HE
        HE  = HC - H
        HHH = HA * KHDOT
        HA  = TRNFR(1,2,Ø.2,Z,T.H)
CONTROL FINTIM=1.Ø,DELT=Ø.ØØ5
SAVE ...
PRINT Ø.2ØØ,PHI,THDOT,HC,H
GRAPH(SE=TEK618) TIME(N1=12,L1=1,UN=SECONDS) TH( UN=DEGREES)
LABEL COLLECTIVE PITCH TIME RESPONSE
GRAPH(SE=TEK618) PHI(N12Ø,UN=DEGREES) THDOT
LABLE COLLECTIVE PHASE PLANE DIAGRAM
END
STOP
```

APPENDIX C

COUPLED LONGITUDINAL MODEL IODE RESPONSE PROGRAM

```
----SPECIFICATIONS----

VARIABLES & INITIAL CONDITIONS
X = Ø.ØØØØØØØØØØE+ØØ
U = Ø.ØØØØØØØØØØE+ØØ
H = Ø.ØØØØØØØØØØE+ØØ
W = Ø.ØØØØØØØØØØE+ØØ
Q = Ø.ØØØØØØØØØØE+ØØ
TH = Ø.ØØØØØØØØØØE+ØØ
THFB = Ø.ØØØØØØØØØØE+ØØ
B = Ø.ØØØØØØØØØØE+ØØ
THC = Ø.ØØØØØØØØØØE+ØØ
TIME = Ø.ØØØØØØØØØØE+ØØ

CONSTANTS:
XC = 5.ØØØØ.ØØØØØØ
HC = 5ØØ.ØØØØØØØØØ

SPECIAL FUNCTIONS:
VP = -Ø.1Ø4*(X-XC)-Ø.2Ø5*U
VC = -Ø.191*(H-HC)+Ø.Ø864*W-5.8776*TH

DERIVATIVES:
D(X /D(TIME) = =
    U
D(U /D(TIME) = =
    -Ø.Ø52*U+2.22*Q-32.2*TH+57.5*B+8.59*THC
D(H /D(TIME) = =
    -1.Ø*W+34.Ø*TH
D(W /D(TIME) = =
    -Ø.34*U-Ø.563*W+34.Ø*Q+25.Ø*B-4Ø9.Ø*THC
D(Q /D(TIME) = =
    Ø.Ø319*U-Ø.ØØ455*Q-1.59*TH-4Ø.9*B+1.48*THC
D(TH /D(TIME) = =
    Q
D(THFB /D(TIME) = =
    34.5*Q+181.Ø*TH-12.5*THFB
D(B /D(TIME) = =
    4.91*THFB-46.3*B+1Ø.5*VP
D(THC /D(TIME ) = =
    -47.Ø*THC+4.64*VC

END CALCULATION WHEN TIME .GE. 25.ØØØØ
```

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